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Integrated climate modelling at the Kiel Institute for World Economics: The DART Model and its applications

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**Integrated Climate Modelling at the
Kiel Institute for World Economics**

The DART Model and its Applications

Paper prepared for the 1st International Workshop on

Integrated Climate Models:

An interdisciplinary assessment of climate impacts and policies

October 2nd - 3rd, 2003

ITCP Trieste, Italy

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1 Introduction

Throughout the past two decades many applied models have contributed to the economic analysis of the global warming problem. The focus is mostly on the assessment of abatement costs associated with a given reduction target, as these can be quantified relatively easily. In contrast, the identification and quantification of abatement benefits, i.e. avoided damages of global warming, pose serious analytical and empirical problems since it requires an integration of economic and natural science considerations. Nordhaus (1991) was the first to apply an empirical optimization approach where both costs and benefits of abatement are quantified by introducing the concept of a greenhouse gas damage function. This damage function is the counterpart of the abatement cost function and describes the costs that accrue to society from climate change through for example impacts on crop yields of land loss to oceans. Nordhaus obtains an aggregate damage estimate in terms of percentages of GDP by summing up impact estimates for different categories at local level. The main shortcoming of this so-called *enumerative approach* is that the summation of estimates from partial equilibrium studies neglects the linkages between the economy and the climate change impacts. These are important as production and consumptions structures adjust to the changing conditions. Consumers, for example, change their demand for energy used for heating or cooling and farmers adjust their crop mix to the new climatic conditions. Adaptation also effects the national and even international division of labor when trade flows and foreign direct investment react to emerging scarcities of goods and factors. A second problem is, that prices react to goods and services becoming more costly through climate change. Monetary estimates of climate impacts based on existing prices thus underestimate welfare effects.

In a computable general equilibrium (CGE) model these problems can be avoided since it has the capacity to represent all relevant components of an economy and to model explicitly their interrelationships. A CGE model can incorporate direct climate impacts on production and consumption and derive the indirect impacts (so-called second order effects) for all components of the economy. Furthermore, the CGE framework avoids the use of questionable price tags on climate impacts because economic agents are modelled in terms of physical units. Finally, CGEs can be calibrated to regional data bases which allows the choice of an appropriate regional dimension of climate change impact analysis. Since CGEs have also been used for the assessment of abatement cost, their use for impact assessment opens the opportunity to integrate cost and benefit analysis in the same modelling framework to obtain consistent results.

The dynamic, global, regionally and sectorally disaggregated CGE-model DART was developed at the Kiel Institute for World Economics for the purpose of assessing the

impacts of climate change and climate policy. DART was for example used to assess prevailing issues in the debate of the Kyoto Protocol such as different regimes for international emissions trading and to investigate the implications of different degrees of capital mobility. One challenging project that is at the heart of this paper was to integrate economic impacts of climate change into the DART model using data provided by an ocean-atmosphere model. Even though there are in theory many possibilities to include economic impacts of climate change into CGE models (see Deke et al. 2001), the main practical problem is to convert changes in climatic variables such as temperature and precipitation into economic damages. As empirical data are more or less restricted to the impacts on yield changes and to sea-level rise, only these two kinds of damages are included in DART.

The aim of this paper is to give an overview over the DART model and its applications. The main focus is on the implementation of climate impacts into DART in the course of coupling DART to the ocean-atmosphere model and on the associated empirical problems. The basic DART model and some applications are presented in the next section. Section 3 describes in detail how the economic impacts of climate change on the agricultural sector and the impact of sea level rise are implemented in DART. Section 4 presents selected simulation results. Section 5 concludes.

2 The DART Model and its applications

2.1 The Basic DART Model

The DART (**D**ynamic **A**ppplied **R**egional **T**rade)Model is a multi-region, multi-sector recursive dynamic CGE model of the world economy covering in its standard version 11 regions and 11 sectors and the production factors labor, capital and land. The sectoral aggregation covers among others the main energy sectors. The economic structure is fully specified for each region and covers production and final consumption. Each market is perfectly competitive. Output and factor prices are fully flexible. For each region the model incorporates two types of agents: producers, distinguished by production sector and the final consumer which comprises a representative household and the government.

Producer behavior is derived from cost minimization for a given output. Each industry is characterized by a multi-level nested separable constant elasticity of substitution (CES) function that describes the technological substitution possibilities between a value added composite of capital and labor, energy and non-energy intermediate inputs in domestic production. The distinction between energy and non-energy intermediate products is useful in the context of climate policies.

Table 1: Dimensions of DART97

Production sectors/Commodities	
Energy Sectors	Non-Energy Sectors
COL Coal	AGR Agricultural Production
CRU Crude Oil	IMS Iron Metal Steal
GAS Natural Gas	CPP Chemicals, Rubber, Paper, Plastic Products
OIL Refined Oil Production	Y Other Manufactures & Services
EGW Electricity	TRN Transport Industries
Countries and regions	
Annex B	Non-Annex B
NAM North America (USA, Canada)	LAM Latin America
WEU West European Union	IND India
PAO Pacific OECD (Australia, New Zealand, Japan)	CPA China, Hong Kong
FSU Former Soviet Union	PAS Pacific Asia
	MEA Middle East, North Africa
	AFR Sub-Saharan Africa
	ROW Rest of the World
Production Factors	
LAB Labor	LND Land
CAP Capital	

The **final consumer** receives all income generated by providing primary factors to the production process. A fixed share of income is saved in each time period. These saving are invested in the production sectors. The disposable income (net of savings and taxes) is then used for maximizing utility by purchasing goods. The expenditure function is modelled as a CES composite which combines consumption of an energy aggregate and a non-energy-bundle. Within the non-energy consumption composite, substitution possibilities are characterized by a Cobb-Douglas function of Armington goods.

To analyze climate policies **CO₂ emissions** resulting from the burning of fossil fuels are calculated for final and intermediate energy consumption.

All regions are linked by bilateral **trade** flows and all goods, except the investment good, are traded among regions. Trade flows are modelled following the Armington-assumption and domestic and foreign goods are imperfect substitutes distinguished by country of origin. Import demand is a three stage, nested separable CES cost resp. expenditure function. On the first level domestic and imported goods are substitutes. Imports are itself a composite of the sum of exports and transportation costs from each other. On the export side, the Armington assumption applies to final output of the industry sectors destined for domestic and international markets.

Factor markets are perfectly competitive and full employment of all factors is assumed. Labor is assumed to be a homogenous good, mobile across industries within regions but internationally immobile. In the basic version of the DART model capital is inter-sectorally but not internationally mobile. Capital stock is given at the beginning of each time period and results from the capital accumulation equation. The primary factor land is only used in agricultural sectors and exogenously given.

2.2 Dynamics

The DART model is recursive-dynamic, meaning that it solves for a sequence of static one-period equilibria for future time periods connected through capital accumulation. The major driving exogenous factors of the model dynamics are population change, the rate of labor productivity growth, the change in human capital, the savings rate, the gross rate of return on capital, and thus the endogenous rate of capital accumulation. The savings behavior of regional households is characterized by a constant savings rate over time. The endowment of land is assumed to be constant over time.

Labor supply considers human capital accumulation and is, therefore, measured in efficiency units, $L_{r,t}$. It evolves exogenously over time. Hence, labor supply for each region r at the beginning of time period $t+1$ is given by:

$$\bar{L}_{r,t+1} = \bar{L}_{r,t} * (1 + gp_{r,t} + ga_{r,t} + gh_r) \quad (1)$$

where the bar denotes exogenous variables. An increase of effective labor implies either growth of the human capital accumulated per physical unit of labor, gh_r , population growth gp_r or total factor productivity ga_r or the sum of all.

The version of the DART model used for this paper assumes constant, but regionally different labor productivity improvement rates, ga_r , constant but regionally different growth rates of human capital, gh_r , which stem from Hall and Jones (1999), and declining population growth rates over time, $gp_{r,t}$, according to the World Bank population growth projections. Because of the lack of data for the evolution of the labor participation rate in the future the growth rate of population instead of the labor force is used implying that the labor participation rate is constant over time.

Current period's investment augments the capital stock in the next period. The aggregated regional capital stock, Kst at period t is updated by an accumulation function equating the next-period capital stock, Kst_{t+1} , to the sum of the depreciated capital stock of the current period and the current period's physical quantity of investment, $Iq_{r,t}$. The equation of motion for capital stock $Kst_{r,t+1}$ in region r is given by:

$$Kst_{r,t+1} = (1 - \delta_t) * Kst_{r,t} + Iq_{r,t} \quad (2)$$

where δ_t denotes the exogenously given constant depreciation rate. The allocation of capital among sectors follows from the intra-period optimization of the firms.

For a more detailed description of the DART-Model see Springer (2002), Klepper, Peterson, and Springer (2003).

2.3 The Kyoto Protocol and Emissions Trading

One of the first applications of the DART model was to simulate the implementation of the Kyoto Protocol in which the industrialized countries listed in Annex B of the Protocol agreed to cut down their greenhouse gas emissions by on average 5.2 % relative to the 1990 levels and until 2012. The scenario that was first analyzed was that all Annex B countries unilaterally reduce their CO₂-emissions as specified in the Protocol. The simulations show that economic activity is restructured away from energy towards capital and labor. Energy-intensive sectors shrink, while sectors that are more labor- or capital-intensive expand. An indirect effect called leakage-effect is a fall in world energy prices that leads to higher fossil fuel demand in non-abating countries and thus a specialization in more energy-intensive goods. The Kyoto Protocol also affects overall income and growth rates of GDP. The reduced energy use of industrialized countries slows down growth in regions that are major exporters of fossil fuels and thus to some extent also affect regions, which supply exports to these countries. On the other hand, non-abating countries in general gain competitiveness in energy-intensive sectors. The numerical simulations show that the energy exporting regions Middle East and Russia but to a smaller degree, also Latin America and Africa lose welfare (5-10 % 1-2 %). In China, India and the newly industrialized countries in Asia that are energy importers and thus gain from lower energy prices welfare increases by 1 to 2 %. The Annex B countries lose around 2 % of welfare. Only in the Pacific OECD countries (Japan, Australia, New Zealand) whose benchmark emissions stay relatively constant, the Kyoto restrictions have almost no welfare effect (Springer 2002).

At the beginning of the new millennium, interest in the flexible mechanisms to reach the Kyoto targets grew. International emissions trading as an efficient instrument to reach the overall target at minimal cost moved to the political agendas. Consequently,

the DART model was extended and used to analyze prevailing issues associated with international emissions trading.

One application (Klepper and Peterson 2002a; Klepper and Peterson 2002b) was to analyze the likely amount of excess permits ('hot-air') in the countries of the former Eastern Block and the institutional details of permit allocation in the economies with hot-air that also determines whether these countries can use market power on the permit market. Simulating three likely institutional setups in the hot-air economies that differ with respect to who is allowed to trade in these economies (firms and/or governments) and with respect to the amount of permits allocated to the firms show that depending on the setting optimal hot-air supplies vary between almost 0 % and 35 % of the available hot-air in a trading system without the USA that withdrew from the Kyoto Protocol in 2001. The objective function of the government of hot-air economies influences this variation. Under welfare maximization more hot-air is sold than under revenue maximization, mainly because hot-air supplies can be used as trade policies for energy and energy-intensive sectors.

The importance of world energy prices is at the core of another analysis (Klepper and Peterson 2003) on marginal abatement cost curves. The marginal abatement cost (MAC) for emissions in a specific region represent the cost of the last tonne of emissions mitigation in order to fulfill a certain reduction target. The cost for different targets taken together form the marginal abatement cost curve (MACC). Many partial equilibrium analysis of emissions trading use MACCs that differ from country to country. All studies rely on the result of Ellerman and Decaux (1998) that each region has a unique MACC independent of the behavior of the rest of the world. Theoretically though, MACCs depend amongst others on energy prices (Klepper and Peterson 2003). Thus, if changes in the abatement level in one country can affect the world energy prices (which is for example true for the US withdrawal from the Kyoto Protocol), this also affects the MACCs of the remaining countries. Simulations with DART show that the relative difference in MACs can reach 75 % for low abatement levels. After the recent developments we can expect that the actual Kyoto targets are quite low and thus will be located in a range where the differences in the MACCs cannot be neglected.

2.4 Capital Mobility

In a globalizing world, effects of greenhouse gas emissions abatement by one subset of countries will automatically spill over to countries that may or may not undertake abatement efforts themselves. The two main channels for these spillovers are trade in goods and capital flows between countries, for example through foreign direct investment (FDI). Even though theoretically, both are perfect substitutes with regard to

prices and welfare, there are many cases in which the substitutability between trade in goods and factor mobility does not hold (Springer 2000). To simulate the impact of increasing international capital mobility on the effects of international climate policies numerically, different degrees of capital mobility were implemented in DART. The model can now differentiate between perfect capital mobility, mobility of new investment but immobility of already installed but not depreciated capital (vintage model) and completely immobile capital (basic scenario). In addition, in two model versions of imperfect capital mobility, the income from FDI is transferred back to the country where the capital was raised. This makes it possible to model portfolio decisions of capital owners and to take account of the empirical fact that there exist different degrees of capital mobility between industrialized and developing countries.

The simulation results (see Springer 2002) show that international capital mobility indeed affects economic growth and international climate policy. In the benchmark without climate policy, more capital mobility increases welfare especially in developing countries that will face an increasing capital shortage in the future. Complete capital mobility - a rather unrealistic scenario - leads to sizeable welfare gains. Scenarios of imperfect capital mobility that take into account actual regional preferences for FDI, have much smaller effects as FDI mainly goes to industrialized countries, whereas the capital shortage will occur in the Third World. The simulations thus confirm that a further liberalization of FDI in developing countries would lead to significant welfare gains. This result though does not simply translate to similar effects for climate policies. Comparing the different scenarios of capital mobility for the Kyoto Protocol, implemented through unilateral emission reductions in the Annex B countries, reveals that in contrary, more capital mobility increases the cost of reducing emissions. One reason is that the unilateral commitments lead to an artificial comparative advantage of developing countries in capital- and energy-intensive sectors. Capital mobility increases this advantage and accelerates FDI in these countries. Hence, distortions in the international division of labor increase, reducing welfare. In addition, FDI increases energy-intensive production in the non-abating countries, leading to higher emissions. Reaching a specific emission target therefore requires even stronger restrictions within the industrialized countries and thus increased economic costs. Alternatively, with more capital mobility and the same targets in place, overall reductions decrease.

3 Economic Impacts of Climate Change in DART

The remaining paper focuses on how DART was coupled with an atmosphere-ocean model of the Max-Planck Institute for Meteorology in Hamburg. Generally, two steps are necessary to implement climate impacts into a CGE model. First, one needs data

on relevant climate variables that impact human living conditions, typically change in the near-surface temperature, changes in precipitation and sea-level changes. These data have to be in the same regional aggregation that is used in the CGE model and in addition generated for scenarios that are consistent with the CGE benchmarks. Second, and this is the main and more difficult task, these climatic variables have to be related to climate impacts. Kurtze and Springer (1999) describe different possibilities for integrating climate variables into the CGE framework. After choosing one of these options the associated parameters or changes in parameters due to climate change have to be quantified. Since prices and therefore economic damages are endogenous to CGE models, region-specific impact functions have to be specified on the basis of studies which examine the physical impact of climate change on the economy. The majority of existing studies on physical impacts deal with the agricultural sector which is especially climate sensitive. There exist very few quantitative studies that analyze the impact of climate change on other sectors or on final demand¹.

The DART model thus confines climate impacts to the agricultural sector and in additions deals with the economic costs of sea-level rise. Climate change impacts are integrated into DART by means of region-specific impact functions that relate the projections of the climate parameters provided by the climate model to the impact on factor endowments or decisions of economic agents. The climate model computes regional paths of temperature, precipitation and sea level rise for different CO₂ emission scenarios that have been generated with the DART model itself². The remaining paper is a summary of the working paper by Deke et al. (2001). Large parts rely on the descriptions in this paper³.

3.1 Impacts on the Agricultural Sector

The future impact of climate change on agriculture is supposed to differ by region. While in some regions agricultural production may decrease, for example due to decreasing crop productivity or losses in acreage, the agricultural sectors in other regions may benefit from more humid climate. A CGE framework can capture climate-induced changes on the supply side of the economy that result from changes in relative prices. What can not be captured are reactions from producers that change their behavior for example through a variation of cultivation activities or change in crops grown. Information on the magnitude of qualitative and quantitative changes in the production function of the agricultural sector can be derived from physical impact studies. These

¹For a more detailed discussion of numerical implementation of climate impacts into CGE models see Kurtze and Springer (1999)

²For a more detailed description of the climate model see Deke et al. (2001), chapter 3.

³This is especially true for the part on sea-level rise originating from C. Kasten.

studies deal with different issues, such as shifts of cropping zones, the assessment of changes in crop yields or the analysis of the effects of income and employment in the agricultural sector (Feenstra et al. 1998). Since sectoral adaption to climate change is endogenously determined in the CGE framework, only those impact studies which deal with yield changes and which do not consider overall economic reactions are appropriate for determining the impact functions. All studies use data derived from meteorological simulation models (the General Circulation Models GCMs). The published results of the GCMs mainly document changes in average annual mean temperature in degrees and percentage changes of the annual amount of precipitation. For this reason the same variables are used in DART. Finally, percentage changes in annual yield per hectare are determined by using different GCM scenarios for the two climatic variables.

The impact function

To implement impacts into a CGE models, the information from the impact studies have to be translated into a continuous functional relationship between the yield change, temperature change and change in precipitation. In DART a simple linear relationship of the form⁴

$$\frac{dq}{q} = \alpha_1 * dT + \alpha_2 \frac{dP}{P} \quad (3)$$

is used where $\frac{dq}{q}$ are the relative changes in yield per hectare in percent, dT is the absolute change in temperature in degree Celsius, $\frac{dP}{P}$ are relative changes in precipitation and α_1, α_2 are the climate impact parameters.

Such a linear relationship implies that the more temperature and precipitation vary, the more crop yields are affected. This specification can only hold for small perturbations since it can be observed, that yields of certain crops sometimes decrease dramatically one temperature or precipitation cross a previously unknown threshold. In this case already small changes in climate variables cause large non-linear changes in yields (Parry 1990). But as the time horizon of the economic model is relatively short compared with the usual time horizon of climate models and as the predicted climate change relevant for the short- to medium term economic model do not produce big climate changes, it is reasonable to assume that the thresholds will not be reached. Furthermore, equation 3 explains relative changes in yields by relative changes in precipitation but *absolute* changes in temperature. This specification is necessary since data on temperature variations are also given in absolute numbers in the impact studies.

⁴The interaction between temperature and precipitation is typically supposed to have some impact on yield changes, too. However, in a least-square estimation using data from impact studies for the US and Canada, the estimated interaction coefficient is not significant. Due to limited data, it is not possible to estimate region-specific types of impact functions for any other region. Therefore, the linear relationship is assumed to hold for all regions.

Integrating the impact function into the CGE-framework

For a specification in DART it is assumed that the yield changes result from changes in the productivity of land. Hence, the yield changes found in the climate impact literature have to be transformed into changes of productivity of land ⁵.

Let $V_t(T_t, P_t)$ be land in efficiency units which depends on temperature T and precipitation P . Absolute variations in land (dV) are thus explained by variations in climate variables T and P :

$$dV = \frac{\delta V}{\delta T} * dT + \frac{\delta V}{\delta P} * dP \quad (4)$$

The partial derivatives $\frac{\delta V}{\delta T}$, $\frac{\delta V}{\delta P}$ can be determined by using the results from the impact studies and the production function of the agricultural sector from the model. Since in the existing aggregation of the DART model, different commodities like crops, livestock, products and processed goods are aggregated to only one agricultural composite, it is also necessary to employ some simplifying assumptions on the production of the sub-commodities to derive output changes of the total agricultural sector from changes in crop yields only. A detailed derivation that results in equation 5, is found in the appendix

$$dV = \lambda * \left(\alpha_1 * dT + \alpha_2 * \frac{dp}{P} \right) \quad (5)$$

The term in brackets is identical with the right hand side of equation 3. λ is a scaling factor that entails the share of crop yields on total agricultural output and technological conditions in the agricultural sector.

Numerical specification of impact parameters

The parametrization of the impact function with respect to α_1 and α_2 must be done in spite of a number of data problems. First, the number of impact studies on crop yields is very limited for some regions. Second, the studies are usually focused on one particular crop in a single and often narrowly defined geographical area. And third, in some impact studies, the climatic data are only incompletely documented so that analogue temperature and precipitation data from other studies had to be assumed, which may potentially lead to some distortions in the underlying data. Due to lack of sufficient data, it has been only possible to econometrically estimate the climate parameters for the region North America. For the other regions the few existing studies were used to derive a range of conceivable values for the impact parameters. See Deke et al. (2001) for methodological details. The studies that were used are summarized in Table 2.

⁵As land is used only in the agricultural sector changes in land endowments, or land productivity respectively, are sector specific changes.

Table 2: List of employed impact studies

Region	Impact Studies
North America	Adams (1989), Barry/Gen (1992), Kaiser (1991), Kokoski (1994), Mooney/Arthur (1990), Parry (1990), Schimmelpfennig et al. (1996), Smit et al. (1989), Williams et al. (1988)
Western Europe	Bergthorsson et al. (1988), Delecolle et al. (1994), Iglesias (1995), Santer (1985)
Former Soviet Union	Fischer et al. (1996), Menzhulin et al. (1994)
Pacific Asia, OECD	Baer et al. (1994), Fischer et al. (1996), IPCC (1996), Matthews et al. (1994)
Pacific Asia	Escano/Buendia (1994), IPCC (1996), Matthews et al. (1995), Tongyai (1994)
China	Fischer et al. (1996), IPCC (1996), Jin et al. (1994), Matthews et al. (1995)
India	Gadgil et al. (1988), Kokoski (1994), Karim et al. (1994), Quershii/Iglesias (1994)
Middle East & North Africa	Eid (1994), Onyeji/Fischer (1994), Strzepek et al. (1994)
Subsahran Africa	Akong' et al. (1988), Muchena (1994)
Latin America	de Siqueria et al. (1994), Fischer et al. (1996), Liverman (1992)

The parameter values with the strongest (negative) influence are called the high impact case, and those with the weakest or even positive influence the low impact case. The impact parameters for the two extremes are given in Table 3.

Columns 2 and 3 show the percentage change in crop yields if temperature rises by one degree keeping the amount of rainfall constant. The "high impact" parameters (cf. col. 2) capture the situation when crops show the highest vulnerability to temperature change, while the "low impact" parameter (cf. col. 3) describe changes in crop yield under the most favorable conditions, for example due to an increasing CO₂-concentrations in the atmosphere biomass production of plants relatively increases and hence negative impacts on plant growth caused by drought, heat stress, etc. may be partly offset or even overcompensated. Since the available impact studies for India and Pacific Asia show substantial but very diverging yield changes the range between lower and upper limit is significantly wider than for the other regions. Columns 4 and 5 describe the percentage change in crop yields when the amount of precipitation increases by one percent keeping the annual mean temperature constant. Note that the parameters values for regions with subtropical and tropical climate conditions show a negative sign (cf. col.

Table 3: Climate Impact Parameters

Region	% Yield changes rel. to +1% change in			
	temperature (α_1)		precipitation (α_2)	
	high	low	high	low
North America	-9.0	-1.0	0.4	1.5
Western Europe	-6.5	5.4	0.0	1.5
Former Soviet Union	-12.5	0.0	0.0	3.0
Pacific OECD	-9.0	5.3	-0.3	2.8
Pacific Asia	-13.8	10.0	-0.7	0.0
China	-19.0	0.0	-3.5	3.8
India	-16.4	14.0	-2.0	3.2
Mid East & N'Africa	-10.7	-4.0	0.0	0.1
Sub Saharan Africa	-6.8	3.6	-3.0	1.5
Latin America	-15.5	0.2	-1.3	1.1
Rest of the World	-11.1	2.8	-1.4	1.2

4). The implied decrease in crops associated with an increase in average precipitation can be attributed to more frequent incidences of floods and rain storms. Vice versa, in the case of a positive sign of the precipitation parameter, negative effects on crop yields due to inundation may be overcompensated by positive effects due to less droughts.

3.2 The Impacts of Sea-Level Rise

Another consequence of climate change is the likely increase in sea-level. The increase in global mean temperatures causes the thermal expansion of ocean water and the melting of land-based ice sheets and mountain glaciers which in turn can lead to an increase in sea-level (Cline 1992, 107), (den Elzen and Rotmans 1992). Sea-level rise has a direct physical impact on coastal zones and islands. First, the retreat of the shoreline causes the inundation of land (wetland and dryland) and physical assets. Second, a higher sea-level enhances the vulnerability of coastal zones to flooding, and third, their vulnerability to the intrusion of salt water (Titus et al. 1991). If people anticipate the physical impact of sea-level rise, they are likely to adapt by taking protection measures such as building or raising dikes and nourishing and elevating beaches.

There is a variety of regional studies which analyze the physical impact of sea-level rise and potential adaptation measures. The most comprehensive studies have been conducted for the United States (e.g Titus et al. 1991; Yohe et al. 1996) and the Netherlands (e.g. example Den Elzen and Rotmans 1992). Further studies refer to

small island states, which are particularly threatened by sea-level rise (cf. e.g. Cline 1992: 111; IPCC 1996: Chapter 9). On the one hand, the studies evaluate the physical impact by quantifying the damages that would result under different projections of sea-level rise. On the other hand they evaluate adaptation options by comparing the costs of different protection measures for a given projection of sea-level rise.

Some damages can be easily quantified, at least in terms of physical units if not in terms of monetary values: the acreage of lost dryland and wetland, the loss of physical assets and the people displaced or otherwise affected. Other damages are more difficult to quantify. The increasing vulnerability of coastal zones to flooding and salt water intrusion, for instance, is difficult to capture in numerical values. Also the monetary evaluation of land losses can be difficult: some coastal areas are not directly used for economic purposes but provide ecosystem services which are hard to quantify. Because the damages from sea-level rise are difficult to evaluate they are often quantified in terms of physical units, such as acres of lost land or number of species extinct, rather than in terms of monetary values.

Protection measures are evaluated in two ways. Some studies derive the optimal level of protection by comparing the monetary values of damages to the costs of the protection measures that would be necessary to avoid these damages (e.g. Den Elzen and Rotmans 1992; Fankhauser 1994). Other studies calculate the costs of different protection scenarios where, for instance, only developed areas, only densely populated areas, or all threatened areas are protected (e.g. Titus et al. 1991).

Introducing the impact of sea-level rise into the DART model

Theoretically, both, the direct physical impact of sea-level rise and the option of protection can be incorporated in a CGE framework to calculate the optimal level of protection. In practice, the information necessary for the incorporation are hard to obtain (Deke et al. 2001). Therefore, it is assumed in DART that all coastal zones threatened by sea-level rise are actually protected. This implies that protection costs are much lower than expected damages and that it is, therefore, efficient to protect all land which is a plausible approximation. Fankhauser, for instance, concludes from its optimization analysis for the OECD countries that "... the optimal degree of protection will vary between about 50% to 80% for open coasts and beaches ..." and that "Cities and harbors are almost invariably protected to the full." (Fankhauser 1994, 31).

In DART, protection measures such as dikes or elevated beaches are not available as inputs for the production of goods. Therefore, annual protection expenditures are modelled as investments in non-productive capital which reduces the savings available for investments in the productive capital stock. More precisely, it is introduced into

DART by modifying equation 2 (cf. section 2) that describes capital stock accumulation in each region.

$$\begin{aligned}
 Kst_{r,t+1} &= (1 - \delta_t) * Kst_{r,t} + Iq_{r,t} - Pc_{r,t} \\
 &= (1 - \delta_t) * Kst_{r,t} + Iq_{r,t} - pscm_r * m_r * GDP_{r,t}
 \end{aligned}
 \tag{6}$$

where $Pc_{r,t}$ is the protection costs in region r in year t, in US\$. To account for the economic growth that is inherent in the recursive-dynamic model, protection costs are related to GDP and it is assumed that the regional ratio $pscm_r$ of protection costs for a 1-meter rise and GDP remains constant over time. Constant absolute monetary values instead of relative GDP shares would result in an ever diminishing cost share for protection from sea-level rise in a growing economy, which does not seem very plausible. $Pc_{r,t}$ is finally obtained by multiplying the protection cost for a 1-m sea-level rise by the sea-level rise m that is calculated in the climate model for different CO₂-emission scenarios in meters.

The chosen approach has the advantage to be manageable from the point of view of data availability. Furthermore, it still allows to use the capacity of a multi-regional framework to derive differences in the ability of the regional economies to cope with the burden of protection costs.

Numerical specification of the parameters

Protection cost studies differ widely with respect to the scenarios of sea-level rise and the methodologies used. The studies used for the implementation in DART rely on a survey of 23 country case studies provided by the Intergovernmental Panel on Climate Change (IPCC 1996). The IPCC results are based on the assumption that the sea-level rises between the present and the year 2100 by 1 meter and in a slow, gradual process. "Adaptation/protection costs" are defined as costs associated with "... defensive measures by which one seeks to maintain shorelines at their present position by either building or strengthening protective structures or by artificially nourishing or maintaining beaches and dunes." (IPCC 1996: 311f.). The IPCC assumes that total protection costs accrue uniformly over 100 years (IPCC 1996: 309).

Total protection costs differ between regions because of differences in the lengths of the coast lines to be protected, the kind of protection measures chosen, and the costs of protection measures. The US, for instance, have a much longer coastline than the Netherlands and have to spend more on protection in absolute terms. Furthermore, people in some countries like the Netherlands have a long experience with protection from the sea. Due to existing know-how and infrastructure the additional protection

needed if the sea-level rises is likely to be less expensive. In developing countries, for instance in Africa, labor and capital used as inputs for the building of dikes or the elevation of beaches are much cheaper than in developed countries such as Japan.

As there are neither a study for each country nor a representative study for each of the DART regions, adjusted estimates from the studies in the IPCC-survey are used. In the case of Western Europe, North America and Pacific Asia OECD, estimates from studies on countries like The Netherlands, the US and Japan were taken as representative for the regions the countries belong to. For the regions Middle East, North African, Latin America and Sub-Saharan Africa the adjusted estimates are derived according to coast-line characteristics. For China, Pacific Asia and India were no studies where available at all, analogies to other regions were used, taking into consideration coast-line characteristics and economic performance. Protection costs for the Former Soviet Union (FSU) and the Rest of the World (ROW) region are set to zero. For the FSU, most of its affected coastline is not used for economic purposes and will probably not be protected. Protection costs for the Baltic states represent only a negligible share of GDP. The ROW Region includes countries with extreme diverse sea-level rise vulnerabilities but considering the highly aggregated scope of the simulation, the economic importance of the highly vulnerable subregions is, however, very limited. Total regional protection costs, are shown in column 1 of Table 4.

Next, annual costs are derived by dividing total costs that accrue from 1990 to 2100 by 110. Finally, GDP values from the benchmark run of DART are used to calculate the regional shares of annual costs in GDP in 1990. The results represent the shares of GDP that have to be spent each year in case of a 1-m rise of the sea-level which occurs gradually between 1990 and 2100 ($pcsm_r$) and are shown in column 3 of Table 4.

Table 4: Protection Costs in the Case of a 1-m Rise in sea level between 1990 and 2100

Region	Total Protection Costs (10^9 1990 US\$)	GDP in 1990 (10^9 1990 US\$)	Ann. Protection Costs as share of GDP (in %)
North America	159	5970	0.02
Western Europe	176	6887	0.02
Pacific OECD	208	3568	0.05
Pacific Asia	156	739	0.19
China	78	353	0.20
India	56.5	208	0.25
Mid East & N'Africa	48.5	573	0.08
Sub Saharan Africa	19	282	0.06
Latin America	13.3	1115	0.01

4 Selected Simulation Results

In this section some selected results of model runs are reported. For more results, see Deke et al. (2001).

4.1 The Economic Impact on Agriculture

In summary, the change in the productivity of land will lead to a reallocation of resources within the agricultural sector and a change in the price of agricultural commodities. These adjustments will as a secondary effect also change the sectoral allocation and, in an open economy, spill over to other regions by changing the trade structures. Since these indirect effects may reduce or enhance the direct effects, numerical simulations are necessary to identify the direction of the impacts. Here, the results of running the DART business as usual scenario with high and low impact parameters in the agricultural sector are presented.

In a first step, one can compute the direct effects of climate impacts on agricultural production under the assumption that no adaptation in the agricultural sector takes place. This output effect of the productivity change of land can be calculated by taking the changes in land productivity from a simulation that includes the impact function for agricultural climate impacts together with data on input quantities for 2030 from the benchmark run without impacts. The calculation results are presented below. They basically confirm the presumption that the direct impact in developing regions is higher than in industrialized regions. In the pessimistic high impact scenario,

Table 5: Relative Changes in Agricultural Output without Adaptation in % in 2030

Region	High impact	Low impact
North America	-1.15	+0.09
Western Europe	-0.78	+0.48
Former Soviet Union	-1.95	+0.97
Pacific OECD	-1.07	+1.65
Pacific Asia	-2.33	+1.45
China	-9.36	+2.71
India	-11.50	+ 11.73
Mid East & N’Africa	-2.22	-0.27
Sub Saharan Africa	-3.50	+1.44
Latin America	-2.91	+0.44
Rest of the World	-4.02	+2.11

there are remarkable immediate reductions for India and China which result from a combination of a high vulnerability of cultural plants and a high proportion on crops in agricultural production. Under the most favorable conditions, i.e. the low impact scenario, agricultural output might grow somewhat in the industrialized countries and somewhat more in the Asian economies. Only the Middle East and North Africa will suffer from climate change.

Next, the impact of climate change on the agricultural sector is computed by taking into account the reallocation of resources and the subsequent changes in commodity prices. The question is to what degree the adaptation will decrease the negative impacts of climate change in the different regions. The economy-wide reallocation of factors of production, the changes in the demand structure, and the adjustment in trade flows together will establish a new equilibrium that can be compared to the benchmark equilibrium without climate change. In Table 6 the general equilibrium effects of climate change on regional welfare are summarized for the high and low impact scenario. The percentage changes are relative to the benchmark scenario without climate change and refer to the year 2030. Not surprisingly, the economic impact on climate-sensitive agricultural sector is stronger than the one on the other sectors.

Table 6: General Equilibrium Effects of Climate Change 2030 in %

Region	$\frac{Import\ Price}{Export\ Price}$		Output in		Output in		Welfare	
	in Agriculture		Agriculture		Other Sectors			
	high	low	high	low	high	low	high	low
North America	0.24	-0.17	0.46	-0.52	-0.04	0.02	-0.15	0.03
Western Europe	0.31	-0.12	0.47	-0.07	-0.07	0.04	-0.14	0.08
Former Soviet Union	0.16	-0.03	-0.67	0.40	-0.14	0.06	-0.34	0.18
Pacific OECD	0.17	0.19	0.17	0.99	-0.10	0.06	-0.23	0.25
Pacific Asia	-0.03	0.13	-1.58	1.16	-0.19	0.10	-0.70	0.36
China	-1.79	0.57	-7.48	2.44	-1.71	0.41	-3.85	1.19
India	-2.27	3.13	-8.36	11.57	-1.55	1.85	-5.32	6.88
Mid East & N'Africa	0.17	-0.50	-1.12	-0.97	-0.25	0.13	-0.67	0.19
Sub Saharan Africa	-0.23	0.16	-2.27	1.21	-0.49	0.21	-1.00	0.52
Latin America	-0.34	0.01	-2.09	0.16	-0.20	0.07	-0.82	0.13
Rest of the World	-0.63	0.30	-3.14	1.80	-0.32	0.13	-1.04	0.56

In the *high* impact scenario, the slight increase in the ratio of import to export prices in the agricultural sector for the OECD countries and the Former Soviet Union indicate that the international competitiveness of their agricultural sector increases. In contrast, regions like India and China which are most strongly affected by climate change will increase the imports of agricultural commodities because prices on world markets de-

crease relative to their domestic prices. Consequently, agricultural production expands somewhat in the OECD despite the negative climate impact and it contracts especially in the most affected regions India and China. For the OECD countries, the economy-wide reallocation and the reaction of the world market for agricultural commodities is strong enough to reverse the originally negative productivity effect on the output (compare Table 5, col. 1, and Table 6, col. 2). This means that additional factors of production will move in the agricultural sector of OECD countries which compensate for the productivity slowdown in such a way that sectoral output overall increases.

In all regions, the immediate climate impact is mitigated through adaptation. The output changes in the other sectors (cf. Table 6, col. 3) show that the compensating factor movements into the agricultural sector will, however, come at a cost: The output in the remaining sectors in the economy will shrink. These effects are very small in the industrialized countries mainly because the agricultural sector is comparatively small such that the factor movements out of industry and services into agriculture have little impact on the rest of the economy.

Furthermore, since relative commodity price on world markets changes in favor of agricultural goods relative to non-agricultural goods, the terms of trade for net-exporting regions of agricultural goods improve. Therefore, net-exporting regions experience a relative gain in welfare. These are primarily developing regions like IDI, CPA, LAM and AFR but also the industrialized region NAM. Vice versa, the terms of trade for net-importing regions of agricultural goods, i.e. WEU, FSU, PAO, PAS, ROW and MEA are deteriorating and are thus contributing to a relative loss in welfare.

In the *low* impact scenario except for the Middle East and North Africa Region, which apparently will suffer from a lack of water, agricultural productivity would increase. However, since the climate impact effect interacts with the world market price effect for agricultural products the welfare effects of the low impact scenario are not the same as the productivity effects. This optimistic scenario increases land productivity on average, hence world production of agricultural commodities increases and prices consequently fall. The resulting shift in world trade flows will have a remarkable effect on the Middle East and North Africa where the regional decline in land productivity is more than compensated by the fall in import prices for agricultural commodities thus resulting in a welfare gain. An opposite effect happens to the net-exporting regions - welfare relatively decreases in these regions since their terms-of-trade declines. Nevertheless, the welfare effect of increased land productivity dominates the terms-of-trade effect so that the net-exporting regions gain in this low impact scenario.

It is altogether evident that the welfare effects of climate change in the period up to the year 2030 remain relatively small. This is mainly due to the fact that strong climate impacts are predicted by climate models for the second half of the 21st century.

4.2 The Economic Impact of Sea-Level Rise

Table 7 summarizes the basic data for the simulation of a rise in sea level with DART. The numbers are measured relative to the benchmark without protection expenditures and refer to the year 2030.

Table 7: The Economic Impact of Protection against Sea-Level Rise in 2030

Region	Capital Stock (%)	Change in		Protection Costs as Share of GDP (%)	Sea-Level Rise 1990-2100 (Meters)
		Rate of Return on Capital (%)	Welfare (%)		
North America	-0.029	0.018	-0.027 (5)	0.003 (7)	0.13
Western Europe	-0.020	0.017	-0.006 (9)	0.003 (7)	0.13
Former Soviet Union	-0.015	0.002	-0.009 (8)	-	-
Pacific OECD	-0.041	0.034	-0.020 (7)	0.007 (6)	0.14
Pacific Asia	-0.614	0.388	-0.309 (1)	0.025 (3)	0.13
China	-0.150	0.158	-0.040 (4)	0.028 (2)	0.14
India	-1.316	1.044	-0.309 (1)	0.035 (1)	0.14
Mid East & N'Africa	-0.112	0.058	-0.087 (2)	0.010 (4)	0.13
Sub Saharan Africa	-0.087	0.057	-0.053 (3)	0.008 (5)	0.13
Latin America	-0.029	0.013	-0.024 (6)	0.001 (8)	0.13
Rest of the World	-0.013	0.015	- 0.009 (8)	-	-

Protection costs are only a tiny share of GDP for several reasons: First, the climate model projects sea-level to rise by only 13 to 14 centimeters over a period of more than one hundred years. These projections lie in the lower region of the range between 9 and 88 cm that was presented in the latest IPCC report (IPCC 2001). It has to be kept in mind, however, that the climate model computes only the thermal expansion of ocean water whereas the impact of the melting of land-based ice sheets and mountain glaciers is neglected. Since the effect of changes in the land-based ice is still subject to debate, the sea-level projections used for our simulations should be regarded as preliminary. Second, it is assumed that the sea-level rises gradually. Consequently, protection measures are taken gradually and costs are spread evenly over the entire period of 110 years of which the economic model considers the first 37 years only. The assumption neglects the possibility of abrupt changes that could occur in the future development of climate and sea-level and which would require protection measures to be taken earlier and to a greater extent than assumed here. Finally, protection costs themselves are subject to uncertainty as they were derived on a very thin data bases (cf. section 3).

The projected increase in sea-level is roughly equal for all regions whereas the direct economic impact varies over the regions: Relatively poor regions have to spend a higher share of their GDP on protection than richer regions. The regions Pacific Asia and Pacific Asia OECD, for instance, have to face absolute protection costs that are in the same order of magnitude (cf. Table 4, col. 1). Since the GDP of the region Pacific Asia OECD is, however, about five times as high as the GDP of the Pacific Asia region (cf. Table 4, col. 2), the shares of GDP the regions have to spend on protection differ substantially.

The direct impact from sea-level protection in DART is the slow-down of capital accumulation because protection expenditures reduce the fraction of savings that is available for capital accumulation. There are then two indirect second order effects of lower savings. First, the slow-down of capital accumulation will weaken economic growth (capital accumulation effect). Second, it leads to different rates of capital accumulation in the regions. This in turn results in different relative scarcities of capital as a factor of production (endowment effect). The change in relative factor endowment induces changes in the composition and the total level of production.

Compared to the case without sea-level rise and protection expenditures, the capital accumulation effect depends on the level of expenditures relative to total savings in the region. The endowment effect also depends on the composition of capital stocks across regions. Columns 1 and 2 in Table 7 show the relative changes of the capital stock and of the rate of return. As expected, capital accumulation is slowed down and because of the increasing scarcity of capital its rate of return increases. It is already evident that the economic effects of investments in protection from sea-level rise are extremely small for all economies overall. This is due to relatively small expenditures (see col. 4 in Table 7). Furthermore, the aggregation of the world economy in 11 regions makes coastal ranges small compared to the economies of the regions. And finally, dramatic local consequences such as the threat to the small island states for which protection might be impossible are ignored.

The small impact on capital accumulation results in even lower welfare costs of the protection measures since the economies can adapt to the increasing scarcity of capital. The adaptive capacity differs across regions as is evident from columns 3 and 4 where the regions are ranked (numbers in brackets) according to protection costs on the one hand and welfare effects on the other. These differences between the ranking in protection costs and welfare effects - although tiny - represent the combined effect of regional as well as international allocation effects of a slightly lower path of investment.

5 Conclusions

The DART model of the Kiel Institute for World Economics is a powerful tool to simulate and assess the implications of different climate policy issues such as emissions trading under the Kyoto Protocol. One especially demanding project was to analyze not only the economic costs of climate policies, but to deal with their economic benefits respectively the economic impacts of climate change. In this context, predictions of an atmosphere-ocean model of the Max-Planck Institute of Meteorology in Hamburg for the climatic parameters change in mean temperature and change in the level of precipitation were translated into economic impacts in the agricultural sector. This was achieved by means of an impact function that translates changes in the climatic variables to changes in the productivity of land. The impact function was constructed on the basis of physical impact studies on yield changes by assuming that these yield changes stem from changes in the productivity of land. In addition, the consequences of the predicted rise in sea-level that was also provided by the climate model were modelled by assuming that potential damages are prevented through appropriate investment. The necessary protection expenditures reduce the fraction of savings available for investment in productive capital.

Despite the many problems encountered in this endeavor, some important insights can be gained. The presented regionally and sectorally disaggregated coupled climate-economy-model is located between the highly aggregated macro-models using damage-functions which derive damages in percent of GDP from predicted changes in climate variables and the detailed models of particular media or regions which can describe the impact of climate change but ignore the economic feedbacks. The DART model is designed to identify these feedback effects and to assess the approximate importance of such effects.

Well aware of all the uncertainties involved there seems to be a significant variation in regional climate impacts and their direct effects of agriculture. More importantly so, the costs of these direct impacts will be significantly lowered through adjustments in the factor allocation within each region. In addition, the world trading system also functions as a buffer which can resolve scarcities, for example in nourishments, through increased international trade. The international adjustments in trade flows to regional disturbances turn out to be an important factor in the assessment of the costs of climate change. The ability of the international economy to adjust to regional disturbances lowers the costs of climate change. Despite the huge uncertainties about the likely impacts of climate change on the agricultural sectors in the different regions of the world it remains true that the developing world is more vulnerable to the negative impacts on agriculture than the industrialized countries.

One of the most serious problems in the coupling of climate models with economic models relates to the time horizons over which these models need to be defined. Whereas climate models necessarily need to be concerned with time frames of centuries, economic growth models can at best present possible scenarios and these only for a few decades. This makes them inherently inappropriate for the assessment of long-term climate change. Yet, there is no better alternative available! As a consequence, the assessment of the economic costs of climate change up to 2030 will be based on rather small climate effects. This, however, is only the beginning of a rising trend of climate change which will continue in the future but of which the costs can not be assessed in a reliable way at the moment. The analysis of the sensitivity of economic effects to climate changes has shown that especially those regions which are most vulnerable to climate change are likely to suffer most from further climate change.

There are many opportunities for improving the results and all disciplines can contribute to that endeavor:

- The regional disaggregation was limited by the ability of climate models to produce reliable regional climate change results. Because of this high scaled regional resolution of the DART-model, less attention is paid to subregions which may be more severely affected than their neighbor regions since data from the climate model and data from impact studies are averaged out across regions. To account for those vulnerable regions of smaller scale with a more detailed regional resolution would cause an increasing need for information about regional climate impacts which cannot be covered by the current impact studies.
- The sectoral disaggregation could be more refined - especially in the agricultural sector - without substantial difficulties. Such finer resolution, however, is only helpful if appropriate impact studies for these more detailed activities were available. So far, this is not the case.
- The time horizon for a meaningful climate impact analysis is limited by the ability to develop reasonable scenarios for long-term economic growth. Research on growth processes is well under way and may lead to better insights. On the other hand, social systems do not follow pre-described rules and shocks external to the economic allocation mechanisms such as political crises, natural disasters, technological breakthroughs, etc. will never be accounted although they can have a major influence on growth paths.
- A major improvement would be the expansion of impacts on agriculture and from sea-level rise to other equally likely important impacts such as health effects, impacts of more extreme weather events, and many more.

Nevertheless, despite the large variance in possible results and our lack of knowledge about the likely distribution of uncertain effects, it is possible that even within a few decades the world might experience significant economic costs of climate change. The precautionary principle would suggest to enact an active climate policy without a definite cost-benefit-analysis (which is impossible at the moment).

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A Appendix

Derivation of the impact function for agriculture

We have chosen a simple linear function for the impacts of change in absolute temperature and change in relative precipitation on yields per hectare:

$$\frac{dq}{q} = \alpha_1 dT + \alpha_2 \frac{dP}{P} \quad (7)$$

Assuming that these yield changes result from changes in the productivity of land, the latter can be derived. One problem is, that empirical studies only deal with crop yields, not with agricultural production in a broad sense as it is specified in the CGE model. Sectoral agricultural output is a composite of several heterogeneous commodities including crops, livestock and processed commodities. Each of these commodities serves both as a commodity for final demand and as intermediate for the production of other agricultural goods. As a result, a climate induced loss in land productivity, expressed by a relative decrease of crop yields per hectare, will also have spill-over effects to the production of the other agricultural goods which employ crops as an intermediate input.

For this relationship of intermediate production it is assumed that crops serve as intermediates in the production of every other agricultural commodity and a limitational Leontief-technology is applied in each of these production processes. The crop production itself depends only on primary inputs and not on any agricultural intermediate. Thus, relative yield change in crops as an input cause identical relative output changes of the produced agricultural commodity and thus the total agricultural sector.

Using the agricultural production function $Y = f(V(T, P), \dots)$ in the CGE model it is now possible to relate yield changes to changes in the productivity of land. Assuming that relative changes in f (which are due to the assumptions on intermediates the same as relative yield changes), are caused by a change in $V(T, P)$ alone, leads to

$$\frac{dq}{q} = \frac{df}{f} = \frac{\frac{\delta f}{\delta V} dV}{f} = \frac{\frac{\delta f}{\delta V} * \left(\frac{\delta V}{\delta T} dT + \frac{\delta V}{\delta P} dP \right)}{f} = V * \epsilon_{Y,V} \left(\frac{\delta V}{\delta T} dT + \frac{\delta V}{\delta P} P \frac{dP}{P} \right) \quad (8)$$

where $\epsilon_{f,V} = \frac{\delta f}{\delta V} \frac{V}{f}$ is the elasticity of agricultural production with respect to changes in the productivity of land. Equation 8 implies for α_1, α_2 from equation 7

$$\alpha_1 = \frac{1}{V} * \epsilon_{f,V} \frac{\delta V}{\delta T} \quad \alpha_2 = \frac{P}{V} * \epsilon_{f,V} \frac{\delta V}{\delta P} \quad (9)$$

and thus rearranging the terms

$$dV(T, P) = \frac{\delta V}{\delta T} dT + \frac{\delta V}{\delta P} dP = \frac{V}{\epsilon_{f,V}} \left(\alpha_1 dT + \alpha_2 \frac{dP}{P} \right) \quad (10)$$

To alleviate the strong assumption that relative output changes in the sectoral output are identical to relative changes in crop production a final correction is made. In the real world, the reduction in sectoral output will probably be lower than the reduction in the crop sector as instead of a limitational a rather substitutional relationship between inputs in the non-crop production is likely and other factors can be substituted for crops. Since the gap between the decline in crops production and the decline of the overall sectoral output is greater, the smaller the share of crops on overall agricultural production, the effect of relative changes in yields per hectare is scaled on the sectoral output by a factor Φ that is the share of crops on total sectoral output in the initial period. This leads to the following equation:

$$dV(T, P) = \Phi \frac{V}{\epsilon_{f,V}} \left(\alpha_1 dT + \alpha_2 \frac{dP}{P} \right) \quad (11)$$

For the implementation into the CGE model it remains to calculate $\epsilon_{f,V}$. In DART, f is a nested CES function. In the top nest, sectoral output results from a limitational production technology of intermediate inputs and a composite input C composed of energy and primary factor inputs. Thus $\epsilon_{f,V}$ is the same as $\frac{dC}{dV} \frac{V}{C}$. In a general equilibrium context $\frac{dC}{dV}$ equals $\frac{p_v}{p_c}$ with p_v the factor price of land and p_c the price of the composite input C and $\epsilon_{f,V} = \frac{p_v V}{p_c C}$ is nothing but the current value share of land in the composite input C .