The costs of climate change in the agricultural sector – A comparison of two calculation approaches

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Executive Summary

Although many different studies exist on the costs of climate change, a useful estimate is difficult to determine because the results differ so widely. Therefore, this thesis scrutinized the reliability of some of the major cost estimates and cost estimate methodologies. It was attempted to improve existing work and the understanding of existing models' results, rather than add another independent new number to the wide range of published estimates of the costs of climate change.

The impact module is one of the most problematic features of climate cost models. Very little comprehensive and reliable knowledge is available, but it has a crucial effect on the final results of climate cost models. In this thesis, the agricultural sector in the impact sections of climate change cost models has been assessed in great detail in order to gain new insights on the reliability, theoretical conception and scope for improvement of impact representation in such models.

Hypothesis 1

The first research question deals with the possibility of delivering reasonably objective information on the costs of climate change with the traditional and widely-used integrated assessment models. Hypothesis 1 is:

> In cost models of climate change, an approach striving for maximal objectivity does not (yet) yield meaningful results for the estimation of the costs of climate change. Apart from the necessity for ethical inputs into the model, this is due to the pervasive uncertainties which force the modeller to introduce his or her own judgement into the model. The extent of this uncertainty is so large, that the claim to objectivity ceases to be meaningful.

To accept or falsify the hypothesis, a detailed uncertainty analysis of the agricultural impact sector in the FUND integrated assessment model was effectuated. FUND was chosen from among the frequently used climate change integrated assessment models as the model founded on the widest range of scientific impact studies. It is therefore argued that other models with a weaker linkage to the impact literature would not perform better with respect to uncertainty in the agricultural impact sector. Similarly, agriculture is an impact category with a comparatively good underlying data basis as well as general inclusion in cost models of climate change.

For the uncertainty analysis, the methodology recommended by the IPCC in their Good Practice Guidelines for National Greenhouse Gas Inventories was used and adapted to the context at hand where necessary. According to this methodology, the different processes contributing to uncertainty of the benchmark impacts in the agricultural sector were identified, assessed and converted into probability distribution functions. The compound uncertainty was derived with help of a Monte Carlo analysis. A numerical assessment of impact extrapolation to higher temperatures was effectuated as well as a qualitative comparison to state of the art literature.

A compound probability distribution function was developed to describe the uncertainty of the impact estimate in FUND. The standard deviation of this probability distribution function of welfare change in the agricultural sector triggered by a 2.5°C warming was between 5 and 27 times the welfare change itself, depending on the region. The 95%-confidence interval therefore encompasses a range 20 to 108 times as big as the absolute welfare changes assumed for a 2.5°C warming in FUND. Figure 0.1 illustrates this wide uncertainty range:

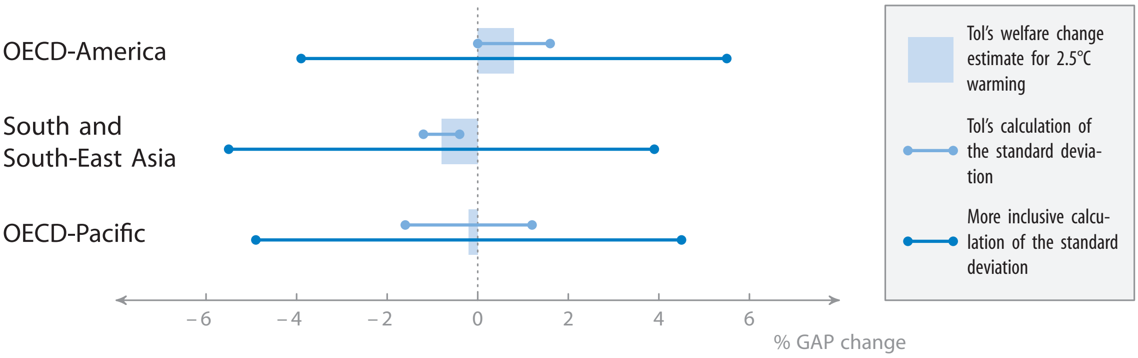

Figure 0.1: The standard deviation compared to the absolute welfare change for 2.5°C warming in FUND

Not all uncertainty types could be quantified, and uncertainty increases further for results where greater warming is analysed. Other major models striving for maximum objectivity can't be expected to perform better.

Hypothesis 1 was therefore accepted. Even though the numerical comparison of costs and benefits of climate change mitigation often appears to be a clear test for rational action, uncertainty is so pervasive that the results cease to be meaningful. Especially where model users are not aware of the uncertainties, they risk drawing wrong conclusions from the models due to the false claim of objectivity.

Hypothesis 2

In the integrated assessment model PAGE, decision analysis was chosen as the theoretical foundation to avoid this false impression of objectivity and certainty. In the second part of the dissertation, this different approach to dealing with the pervasive uncertainty in an integrated assessment model of climate change was assessed.

Decision analysis is a concept that strongly emphasizes the need to openly flag subjective model inputs. Models on this basis do not claim to deliver objective results, but rather try to offer a good basis for rational decision-making based on personal subjective beliefs of model users, both for ethical choices and uncertain input parameters. A model based on this theory should allow decision makers to use the model as an aid to structure ideas and reach a coherent decision based on their own beliefs. The theory was originally developed not for decision problems of whole societies, but for individuals. Difficulties exist in the process of adapting the theory to this different context of climate change.

Hypothesis 2 was formulated as follows:

> To avoid a false impression of objectivity and certainty, decision analysis was chosen as the theoretical foundation for the PAGE integrated assessment model. Although the PAGE model is not subject to some of the common problems in dealing with uncertainty, it does not live up to the standards of its underlying theory: decision analysis.

To test this hypothesis, the general principles of decision analysis were derived from the literature. Then the applicability of these principles to cost-benefit analysis of climate change was tested. Finally, the realisation of the identified principles in the model PAGE2002 was assessed one by one.

In line with the requirements of decision analysis, uncertainty is very openly flagged in PAGE as well as integrated via a probabilistic approach and easy access to the model is assured. But PAGE2002 does not fully live up to the requirement of interactive model building involving both the modeller and the decision makers because the impact representation in PAGE is so abstract that model users can not judge the accuracy according to their own beliefs and opinions. The parameter settings for the impact sector have such an important influence on the final result, that this shortcoming fundamentally impairs the concordance with the principles of decision analysis. Hypothesis 2 was therefore accepted.

Hypothesis 3

Hypothesis 3 deals with the question how scientific work on the costs of climate change can move forward in light of the shortcomings identified in the testing of hypotheses 1 and 2. The question was whether a split of impact representation into single sectors such as the agricultural sector is meaningful to improve the shortcomings of PAGE with respect to the principles of decision analysis:

> An impact representation split into single sectors and founded in up to date scientific impact research as presented in the IPCC Reports helps to overcome the major shortcoming of PAGE with respect to decision analysis. Sectoral impact figures facilitate the decision makers' judgement as to whether they agree with the impact assumptions in the model.

To test hypothesis 3, agricultural impact data for the market sector and for people at risk of hunger was taken from the IPCC Fourth Assessment Report and converted into suitable input data for the PAGE model. The results show that it is possible to develop impact modules that are better in accordance with decision analysis:

The impact representation for the agricultural sector is considered not to be so complicated as to impede comprehensibility of the model. The description in this thesis can be used as a tool to understand the exact development of the numbers; and the foundation on IPCC reports makes it possible to know about the provenance of the data without going into every detail. Ethical assumptions are openly presented and changes to the ethical default assumptions are comparatively easily possible. All in all, it is certainly easier to capture the knowledge and uncertainties of climate change impacts from the analysis based on IPCC data above than in the highly aggregated impact categories of PAGE2002. Thus, the biggest shortcoming of PAGE2002 with respect to decision analysis can be alleviated. From this point of view, a sectoral representation of impacts is a clear improvement.

But quite a number of adaptations were necessary to the data reported by the IPCC to make it an adequate input to the PAGE model, representing the agricultural sector. If all impact sectors were represented in PAGE at an equal level of detail that allows ethical assumptions to be sufficiently separated, the entire model would need to be very large and complex. The single impact study for the agricultural sector is already quite voluminous. A lot of such impact assessments at the necessary level of detail to comply with the principles of decision analysis might surpass the capacity or time constraints of most model users for an understanding of the entire model. This shows very clearly that an improvement with respect to one principle of decision analysis (integrate ethical assumptions and uncertainty beliefs of problem owners) comes at the cost of losing ground with respect to another principle (simplicity).

Furthermore, a thorough sectoral impact representation is a lot of work. It should be decided specifically and in the context of upcoming research questions whether the results that can be obtained from a climate change cost model would be worth such an effort. Hypothesis 3 is hence only accepted with an important limitation: the sectoral impact module is a clear improvement in one sense, but it comes at the price of a significantly more complex model. General recommendations are not adequate. The advantages or disadvantages of a sectoral impact representation must be decided in the light of concrete research questions.

The findings from hypothesis 1 to 3 lead to a paradoxical conclusion: On the one hand, the uncertainty analysis in part 1 supports the assumption that meaningful objectivity of climate cost models is not possible. On the other hand, a climate cost model based on decision analysis – a theory explicitly chosen to accommodate the impossibility of objectivity – also depends on the parameters being chosen as objectively as possible. This is because accordance with the principles of decision analysis is hardly possible without a clear impact representation, and the size of such a model implies that hardly any model user will be able to adapt all assumptions according to personal judgement.

The costs of climate change in the agricultural sector

In order to verify hypothesis 3, a thorough analysis of the costs of climate change in the agricultural sector and of the underlying assumptions was done. The analysis was done separately for market and non-market impacts. For both categories, but especially for non-market impacts, the monetisation of the impact figures is very difficult and fraught with subjectivity.

Non-market impacts

For non-market impacts in the agricultural sector, this thesis focuses on the loss of human lives. It is recommended to use the numbers for additional people dying from the consequences of hunger directly and without a further step of monetisation whenever possible. To express the value of human lives lost in terms of money is very problematic on ethical grounds. The dissent on suitable numbers is even more pronounced when the issue involves world regions with very different levels of per capita income. Table 0.1 displays the expected rise in hunger due to climate change.

Warming	With CO_2-fertilization	Mode	Without CO_2-fertilization	Mean
1.0 °C	5	19	54	26
2.5 °C	23	101	250	125
4.0 °C	93	229	541	288
5.0 °C	148	314	735	399

Table 0.1: Additional millions at risk of hunger due to climate change

The previous caution notwithstanding, a common metric is necessary whenever a direct numerical comparison of the market and the non-market sectors is attempted. It is left for the reader to decide whether knowledge from such a comparison is of any value. A survey of the literature on the costs of a statistical life showed that not enough data is available to use local values and subsequently add a scheme for equity weighting. Therefore available knowledge was used to derive an average global value for a statistical life. This is extremely subjective, and the value was chosen in a way that makes it especially easy for problem owners to integrate their personal assumptions about this measure.

Market impacts

The valuation of market impacts hinges crucially on the assumptions about the effects of global trade, the method to deal with demand not apparent in the demand curve, and the second best measure chosen to approximate the unknown changes in consumer and producer surplus. The latter can not be quantified as the demand and supply curve can not be determined empirically or otherwise in all necessary parts, that is at all points to the left of the market equilibrium. It was shown that changes in gross agricultural product and yield as alternative welfare measures likely underestimate the changes in consumer and producer surplus. In this thesis, the change in productivity was used to approximate welfare changes. This quantity is higher than the gross changes in agricultural product and yield, maybe higher than the loss in consumer and producer surplus. But not all demand is reflected in the demand curve, as an assessment of subsistence farming and low-income consumers showed. This can lead to severe underestimates of true welfare losses.

The inclusion of global trade via global equilibrium models equally underestimates true welfare losses, as poor countries are expected to suffer the biggest yield losses. The productivity change approximation method was chosen as the best method available here to express welfare changes. This method does not provide a perfect approximation, but no other method is better. The overall error induced by this assumption is comparatively insignificant, however, when market and non-market losses are compared or added up. The latter dominate so clearly, that the assumptions about the best welfare measure for market impacts do not significantly influence the final result.

Comparison of market and non-market costs

The comparison of market and non-market monetarized costs shows very clearly that the overall costs of climate change in the agricultural sector are dominated by the costs of hunger. This is even true when the costs of non-fatal hunger are disregarded and with very optimistic assumptions about the hunger caused by climate change. The mean costs of death caused by hunger as calculated with a default value of a statistical life of $ 1 million is about 20 times the mean for market impacts for higher levels of temperature change. For very low levels, even the algebraic sign of the impact is different (a gain for market impacts and a loss for non-market impacts). Including the costs of non-fatal hunger, non-market impacts are estimated at about 30 times the market impacts. It is easy to adapt these results for any other value of a statistical life. Even an extremely low value like $100 000 would suggest that the costs of hunger are two to three times the market costs of climate change in the agricultural sector.

The market costs were also found to be at the higher end of comparable calculations from other models: The losses at 2.5°C warming were calculated to be below 0.05% of GDP in FUND, around 0.2% in DICE, less than 0.1% in a study by Mendelsohn et al. and about 0.26% based on the results of this thesis. Thus the very clear relationship between market and non-market costs found in this thesis is not due to an unusually low value for market costs. Tables 0.2, 0.3, and 0.4 display a few of the monetarized results.

VSL = 1 m US$	Costs of additional deaths due to hunger (billion US$)			
Warming	With CO_2-fertilization	Mode	Without CO_2-fertilization	Mean
1.0 °C	205	735	2046	996
2.5 °C	872	3848	9507	4742
4.0 °C	3534	8700	20556	10930
5.0 °C	5624	11935	27922	15160

Table 0.2: Monetarized impacts of additional deaths due to hunger caused by climate change employing US$ 1 million as the value of a statistical life

	Market impacts (% of gross agricultural product)		
Warming	5th percentile	95th percentile	Mean
1.0 °C	−2.3 %	−9.6 %	−6.1 %
2.5 °C	12.7 %	−1.5 %	5.4 %
4.0 °C	27.5 %	10.9 %	18.9 %
5.0 °C	39.9 %	20.7 %	30.0 %

Table 0.3: Market impacts of climate change in the agricultural sector; for better comparison negative values are gains and positive values are costs of climate change

VSL = 1 m US$	Comparison of impact categories (Mean in billion $\text{US\$}_{2000}$)	
Warming	Market impacts	Death impacts
1.0	−159	996
2.5	140	4742
4.0	494	10930
5.0	782	15160

Table 0.4: Comparison of annual market impacts and monetarized annual costs of additional deaths due to hunger caused by climate change for a value of a statistical life of US$ 1 million (year 2000 values)

While ethical judgements and uncertainties are crucial and not all could be captured in the analysis, the picture is clear enough to call the result robust. Many major uncertainties like the effect of CO_2-fertilization equally affect market and non-market impacts and can not fundamentally change the relationship between the two.

Therefore, accuracy in the calculation of market costs in the agricultural sector is almost irrelevant for cost-benefit analysis when the much more important contribution from the non-market sector to overall costs is neglected and ignored. Still, this is exactly what a lot of traditional climate cost models do. It can not be an argument for neglecting the non-market sector that the costs of hunger are more difficult to calculate than the market costs of yield losses. It is true that the costs of hunger are very difficult to calculate and that they can only be estimated with a high level of uncertainty. It is also true that they are substantially influenced by ethical decisions. But their omission is certainly and beyond doubt a serious error in any calculation of the costs of climate change. It is an advantage of decision analysis that ethical assumptions are openly flagged rather than to drop the impact altogether because objectivity is not possible.

These results suggest that without an assumption about the value of a statistical life and the inclusion of the non-market sector, no meaningful cost-benefit comparison of climate change mitigation levels relying on one metric is possible. The valuation of market costs of climate change is still an interesting piece of information, but it is not useful to compare just a part of the benefits of mitigation to the entire costs and derive from this comparison a recommendation for the optimal level of mitigation.

Whenever it is known whether the omitted impacts are a gain or a loss, cost-benefit analysis can indicate a lower or upper bound of rational mitigation intensity, even without including all major impacts. In case of the agricultural sector, there is very strong evidence that the non-market impacts are negative and very significant. Therefore, models that do not include the non-market impacts of climate change in the agricultural sector show that more mitigation is rational than the cost-benefit analysis suggests at first sight. For a reliable conclusion, it would need to be judged for all other major omitted impacts whether they are a gain or a loss. In a model based on decision analysis, the problem owners should decide what kind of risk or chance they attach to impacts that are so far not recognized at all.

Considering the scope of the difficulties involved, it is recommended not to rely on social cost estimates only for decision making on climate change. Although models of the costs of climate change can provide interesting insight into some economic dimensions of the problem and can be an interesting additional piece of information, they are hardly reliable enough to replace other decision procedures on the optimal level of climate change mitigation.

The impact module in PAGE2002

A lot of detailed knowledge on the possible representation of agricultural impacts in the climate cost model PAGE was gathered in this thesis. From these results as well as from other scientific findings published since the completion of PAGE2002, an evaluation of the model is possible.

Concerning the impact sector in PAGE, the above results suggest that the market impacts have been slightly underestimated in PAGE2002, and the non-market impacts have been significantly underestimated. In PAGE, impact parameters are given as a percentage of GDP for the benchmark warming of 2.5°C. The range for the impact function exponent seems to be remarkably close to reality for non-market impacts, but probably a little too low for market impacts, judging from the IPCC data assessed above. Uncertainty is still high with respect to these parameters, however.

Finally, all major components of the model PAGE were tested against the latest scientific evidence from climate change sciences as compiled in the IPCC Fourth Assessment Report or later publications. It was attempted to judge whether the recent developments in climate sciences rather lead to a more pessimistic or more optimistic outlook on the costs of climate change. Five main scientific fields that are integrated into one model in PAGE were identified:

- The climate module describing the atmospheric processes
- The socio-economic scenario
- Impact representation
- Adaptation assumptions
- Ethical assumptions – utility comparison

Only one factor was found in the whole assessment where recent scientific findings suggest a more optimistic outlook on the costs of climate change: the assumptions with regard to population growth seem to be rather high from the current scientific knowledge. But several scientific developments show that climate change is more dangerous than previously thought: the development of greenhouse gas emissions, the impact parameters in the agricultural sector, the adaptation assumptions and the parameter for climate sensitivity. Therefore the true costs of climate change are very likely even higher than calculated in PAGE2002.

This applies equally to the results presented in the Stern Review. The numbers in the Stern Review have been derived with a combination of PAGE and an add-on called DYNASTY. It was beyond the scope of this dissertation to assess DYNASTY in detail as well. DYNASTY comprises the welfare calculations of the combined model. If in PAGE climate change costs are underestimated, this underestimate enters the DYNASTY model directly and leads to a likewise distortion in the overall result.

The results from this thesis suggest that the estimates presented in the Stern Review have been rather an underestimate of the true costs of climate change. This is very significant: The results from the Stern Review show that a lot more mitigation action than currently implemented is economically rational. Stern and his team have been strongly criticised after the publication of their Review On the Economics of Climate Change for overestimating the costs of climate change. But their clear call for more mitigation is underlined and strengthened by the results of this thesis.

Introduction

1

Climate change has been identified as one of the biggest challenges of this century: with potentially devastating consequences, global both in impact and cause, and penetrating many different aspects of everyday life like heating, transport, electric appliances, agriculture and cooking as well as industrial production.

A lot of thought has been spent on the question how much mitigation action on climate change should be taken, how much adaptation action, and how many residual damages would consequently be accepted. The extremely long-term characteristic of the problem makes a preliminary decision necessary long before the major consequences are visible to their full extent. Therefore modelling the future is an important tool, and Integrated Assessment Models (IAMs) have been frequently employed to explore climate change impacts in a consistent framework and make cost-benefit analyses useful for climate change policy.

1.1 Research question

Today, the available information on climate change impacts is rudimentary compared to the information on mitigation technology (IEA Greenhouse Gas R&D Programme 1999: 2). Although a lot of different studies exist on the costs of climate change, the results differ so widely that a reliable estimate is difficult to deduce from this state of the art. Results for the same level of greenhouse gas concentration differ by the factor 100 and more (Hohmeyer 2001: 34). Rather than add another independent new number to the wide range of published estimates of the costs of climate change, in this thesis the reliability of some of the major cost estimates are scrutinized and it is attempted to improve existing work.

Different factors contribute to this wide disparity in results. One is uncertainty of model inputs and structure, another is the decisive influence of ethical suppositions. No objective answer can be found for the best treatment of the latter. The only possibility to deal with the ethical parameters is to clarify the consequences of different choices and thus allow the model users to apply their own beliefs.

With respect to lack of scientific knowledge, two different basic approaches for dealing with the pervasive uncertainty are identified. First, in integrated assessment models like FUND and DICE, the modellers try to reach the highest possible level of objectivity. Where different studies suggest different input parameters, a set of external conditions is produced to decide which of the study results are worth being an input to the integrated assessment model (e.g. Tol 2002b: 136). To integrate findings from the studies that comply with the criteria, usually a simple average or an adapted average is used (e.g. Tol 2002a: 52). Possible input parameters like damage categories for which only very uncertain estimates or no numbers at all exist are often ignored to maintain the objectivity of the model (e.g. the cost of hunger as is shown in this thesis). Usually in this school of objectivity, point estimates are used as inputs and results.

In this thesis, the approach striving for maximal objectivity is scrutinized with help of an uncertainty analysis. The first hypothesis is:

Hypothesis 1:
In cost models of climate change, an approach striving for maximal objectivity does not (yet) yield meaningful results for the estimation of the costs of climate change. Apart from the necessity for ethical input into the model, this is due to the pervasive uncertainties which force the modeller to introduce his or her own judgement into the model. The extent of this uncertainty is so large, that the claim to objectivity ceases to be meaningful.

In part II of the thesis, one model belonging to a different school of treating uncertainty is equally scrutinized. According to the classification of the modeller (Hope 2008b), the integrated assessment model PAGE is based on a different theoretical foundation: decision analysis. In this theory the possibility of a truly objective analysis is disregarded as impossible and instead a very clear indication and purposeful implementation of subjectivity are recommended.

In this thesis it is tested whether the model PAGE lives up to its own claim to fulfil the basic requirements of decision analysis. The second hypothesis is:

Hypothesis 2:
To avoid a false impression of objectivity and certainty, decision analysis was chosen as the theoretical foundation for the integrated assessment model PAGE. But although the model PAGE is not subject to some of the common problems in dealing with uncertainty, it does not live up to the standards of its underlying theory: decision analysis.

Taking into account the results of testing these two hypotheses, recommendations for the further development and usage of climate change cost models are developed in a third step. It is attempted to sound some possibilities for model improvement. Input figures for the agricultural impact representation in a climate cost model are developed.

1.2 Scope

Integrated assessment models are qua definition very complex constructions, combining information from many different sectors, scientific disciplines and geographical regions. Therefore simplifications can not be avoided. In this thesis, new methodological insight on the modelling of climate change costs shall be gained by taking a very detailed look at a key part of the modelling. To attain a sufficient level of detail and thus gain new methodological insight as well as reliable numerical results, the research is focused on just one impact sector. The choice of the impact module as the focus of research is justified by the fact that the representation of impacts is one of the most difficult tasks while building an integrated assessment model (Nordhaus 2007b: 13,74; Pearce et al. 1996: 183).

The impact sector which was chosen for the detailed analysis is the agricultural sector. It is the impact category with the best underlying data basis and most extensive research according to Nordhaus and Boyer (2000: 74). It is also a sector with a big potential welfare impact, of which monetary impacts are only a part, maybe a minor part. Furthermore, the sector is included in all major integrated assessment models of climate change.

Only the costs of climate change are looked at in the following, not the costs of mitigation. As mentioned above a lot more knowledge exists on the costs of mitigation, therefore the still weaker part of integrated assessment models shall be taken up here.

1.3 Methodology

To accept or falsify hypothesis 1, a detailed uncertainty analysis of the agricultural impact sector in the integrated assessment model FUND is done. FUND was chosen from the frequently used climate change integrated assessment models as the model founded on the widest range of scientific impact studies. It is therefore assumed, that other studies with a less strong linkage to the impact literature would not perform better with respect to uncertainty in the agricultural sector. Similarly, agriculture is an impact category with a comparatively good underlying data basis and was therefore chosen for a detailed analysis.

For the uncertainty assessment, the methodology recommended by the IPCC in their Good Practice Guidelines for National Greenhouse Gas Inventories is used and adapted to the context at hand where necessary. According to this methodology, the different processes contributing to uncertainty of the benchmark impacts in the agricultural sector are identified, assessed and converted into probability distribution functions. The compound uncertainty is derived with help of a Monte Carlo analysis. A numerical assessment of impact extrapolation to higher temperatures is effectuated as well as a qualitative comparison to state of the art knowledge from literature.

Further details on the justification of model choice and the methodology can be found in Part 1 of this thesis.

To test hypothesis 2, the theory of decision analysis is first described and its main principles are derived from literature. Decision analysis was developed for the field of individual decision making. It is discussed, whether this theory can be applied to the decision making of whole societies on the optimal mitigation path with respect to climate change. Necessary adaptations to the theory to allow for the different context are outlined and the merits and remaining limitations discussed. In a third step, the specific application in PAGE2002 is assessed and discussed. For every principle of decision analysis previously identified from the literature research, it is checked whether or to which extent it has been realised in PAGE2002. It is assessed in how far remaining differences between the theoretical concept and the realisation in PAGE2002 impair the concordance of the model with the core idea of decision analysis.

In the third part of the dissertation, the detailed knowledge on the agricultural impact sectors in various integrated assessment models as well as the latest scientific evidence from this sector are used to develop up-to-date cost figures for this sector. The main basis for this impact function is the compilation of scientific evidence in the IPCC Fourth Assessment Report. Both market impacts and additional millions at risk of hunger are assessed. The projections are adapted to the temperature rise assumptions in PAGE to facilitate further use of the results in PAGE. A compilation of many different studies in the IPCC report and results with and without CO_2-fertilization are used to derive probability distribution functions, not just point estimates.

Impacts are derived from the impact literature for different levels of global warming, not just for a benchmark temperature change. However, no impact figures for high levels of warming like 5°C are reported. Therefore extrapolation of the existing data to higher temperatures is necessary. For both impact categories and different study results, several extrapolation methods are tested and presented graphically. The choice is based both on plausibility and coherence with qualitative knowledge on high temperature impacts.

Possibilities for the monetary valuation of these impacts are discussed and for each impact group one methodology is chosen and applied to the impact results derived before. For the valuation of market impacts, changes in consumer and producer surplus are used as a benchmark welfare impact, against which different monetisation methods are compared. Furthermore, qualitative scientific insight is included into the choice of the approach to quantify welfare changes.

For non-market impacts, it is recommended to use the numbers of additional people suffering or even dying from the consequences of hunger directly and without a further step of monetisation, whenever possible. To express the value of human lives lost in terms of money is very problematic on ethical grounds, even more so when the issue involves world regions with very different levels of per capita income.

However, for those who wish to integrate the hunger impacts into a cost-benefit analysis of climate change relying on just one metric, different approaches for a value of a statistical life as well as for benefit transfer to other world regions are discussed. Two different values are used as a sensitivity analysis for this very delicate point. The monetisation allows a rough comparison of the order of magnitude of the market and non-market impacts, giving each reader the possibility to apply their own ethical judgement.

The results are compared to the implicit representation of agriculture in PAGE so far, including adaptation assumptions. The thesis concludes with a check of the major model components of PAGE2002 against recent scientific findings, including the detailed analysis of the agricultural impact sector.

More details on this part of the methodology can be found in Part 3 where the calculations are developed.

Part I

Uncertainty in the representation of agricultural impacts in integrated climate change models

Science is a process striving for objectivity. In this understanding, most integrated assessment models of climate change have been constructed. Although the intellectual challenge is daunting and raising formidable issues of data, modelling, and uncertainty among others, an answer is sought to the question which mitigation path is the most efficient one (Nordhaus and Boyer 2000: 3f). This question can for example be applied to certain international climate policies like the Kyoto Protocol, and the aim is to scientifically and objectively judge the efficiency of such climate regimes. In this part, the possibility of an objective approach to climate cost models is tested for one detailed example.

Uncertainty assessment for the example of the agricultural sector in FUND

2

It can be disputed, whether a neutral and objective answer to the question for the most efficient mitigation pathway is possible in face of the complexity of the issues and the uncertainties involved. In this chapter, hypothesis 1 is tested:

Hypothesis 1:
In cost models of climate change, an approach striving for maximal objectivity does not (yet) yield meaningful results for the estimation of the costs of climate change. Apart from the necessity for ethical input into the model, this is due to the pervasive uncertainties which force the modeller to introduce his or her own judgement into the model. The extent of this uncertainty is so large, that the claim to objectivity ceases to be meaningful.

2.1 State of the art and justification of the impact sector chosen for analysis

One of the most difficult tasks while building an integrated assessment model (IAM) is the representation of impacts (Nordhaus 2007b: 13,74; Pearce et al. 1996: 183). It is interesting to see how different IAMs have approached this challenging task and how big the uncertainties involved are. Some literature exists on the issue. Tol and Fankhauser (1998) compared the impact representation in 19 IAMs and listed features like damage categories considered, spatial detail, functional form of the damage aggregation and how non-linearity for higher temperatures was treated. Warren et al. (2006b) give a much more detailed overview of the impact representation in four of the major IAMs: PAGE (Hope 2006), FUND (Tol 2002a,b), DICE (Nordhaus and Boyer 2000; Nordhaus 2007b) and MERGE (Manne et al. 1995).

In this thesis, the issue is explored in even more detail for the agricultural sector in FUND. FUND was chosen, because of those models named above, it has the most detailed impact sector and it is based on a broader range of field studies than the other IAMs. The impact sector of FUND has also been used as a basis for further modelling (Kemfert 2002: 290). Finally, the consequences of the results from FUND for DICE and PAGE are explored, two other models that are frequently and prominently used in international research (e.g. Warren et al. 2006a: chapters 1 and 3; Kemfert 2002: 282; Keller et al. 2004; Stern 2007: chapter 6.4).

The aim of this paper is to analyse the uncertainty of the representation of agricultural impacts in specific IAMs using the example of FUND, looking at the whole chain from the field study to the final formula in the model. Uncertainty has not been dealt with in detail in the two publications by Tol and Warren. However, information about the reliability of results is essential in order to draw appropriate conclusions from the results. This is especially true, when other people than the original model builders use the results and models for their work. For further thoughts on the value of information about uncertainty see Morgan and Henrion (1990: 43f) and Hiraishi et al. (2000: 6.5). Schimmelpfennig looked at the treatment of uncertainty in economic models of climate change impacts, emphasizing the pivotal role of uncertainty in this field and recommending the use of Monte Carlo analysis (Schimmelpfennig 1996). He did not, however, compare the treatment of uncertainty in specific IAMs.

2.2 Uncertainty assessment – Methodological background

2.2.1 Different types of uncertainty

Uncertainty may arise from many different sources. For the context at hand, they can be attributed to two main groups: uncertainty about quantities and uncertainty about model form and structure (Morgan and Henrion 1990: 47). Uncertainty about the form of the model is harder to quantify (Morgan and Henrion 1990: 67), and this is all the more true for a model of climate change costs where empirical validation can only be done in the far future as the main consequences do not yet exist. However, sometimes uncertainty about the form can be converted into uncertainty about model parameters (Morgan and Henrion 1990: 68).

In this thesis an attempt is made to quantify the uncertainty of the climate change costs in the agricultural sector of FUND. In absence of a better approach, the uncertainty introduced by the model structure is ignored and only the uncertainty implied by imperfect knowledge about the input parameters is quantified.

Wherever possible, uncertainty about the model structure is converted into uncertainty about model parameters and included.

2.2.2 Methodology for the measurement of uncertainty

Morgan and Henrion (1990), (cf. European Commission 1999: chapter 5) give an overview of different methods for quantifying uncertainty in risk and policy analysis. They find that no single method is always the best, but rather that an appropriate approach has to be chosen depending on the nature of the problem and the available information (Morgan and Henrion 1990: 172). The approach which was chosen here resembles the recommendations of the Intergovernmental Panel on Climate Change in chapter 6 of its Good Practice Guidelines for National Greenhouse Gas Inventories (Hiraishi et al. 2000). Hiraishi et al. describe good practice in estimating and reporting uncertainties of emission estimates. But the methodology is also useful for the task of this thesis. Adaptations of the methodology to the special case at hand will be described in chapter 2.4.

The first task of an uncertainty assessment is the identification of the sources of uncertainty in a model. Then a probability density function (PDF) for each of these sources is determined. The probability density functions describe the assumed range of possible values and their respective likelihoods. Ideally, they would be derived from source-specific measured data. But this is hardly ever possible for all uncertainty sources, especially for a model about future, not yet existing conditions like those described in FUND. The pragmatic approach is to use best available estimates: a combination of the available measured data, knowledge transfer and expert judgement (Hiraishi et al. 2000: 6.5).

Characteristics of different continuous probability density functions:

Some probability density functions look different from most others at first sight, like for example the uniform distribution. Others appear more similar for certain parameter settings, like for example the Chi-Square and the Gamma distributions. But in spite of the similarity at first sight, they are adequate for different contexts. An in depth analysis of these probability densities is beyond the scope of this thesis and can be found in any major statistics textbook. Therefore only a very brief overview of a few functions is given here:

Uniform distribution: Every outcome is equally likely. It is appropriate when the user is able and willing to identify a range of possible values, but unable to decide which values are more likely than others. An example could be a leak along a section of pipe.

Exponential distribution: It is for example used for the time gap between the arrival of two clients in a cue; for the service time for one customer or one repair, or for the life time of spare and wear parts. It has the useful quality, that the likelihood of the event occurring (e.g. the next customer entering the shop) is independent of the time that has elapsed since the last event. Therefore it is sometimes called distribution without memory

Normal distribution: This is the most commonly used distribution, because the empirical distribution of data can often be described by a normal distribution. This is usually the case, when a large number of random influences are added, as for example with respect to measurement errors and deviation of average values. The normal distribution is symmetrical. When a set of data is not symmetrical, it is still possible that $\ln x$ is a normal distribution.

Lognormal distribution: Quantities formed from multiplying uncertain quantities tend to be lognormal. If x is lognormally distributed, then $y = \ln x$ is normally distributed.

Student's *t* distribution: It can be applied to the modelling of data that has a higher percentage of outliers compared to the normal distribution.

Triangular distribution: It is used when values towards the middle are considered more likely than the extremes. In addition to being simple, the apparently arbitrary shape can, in some contexts, help to convey the message that the distributions of variables are not precisely known.

(Fahrmeir et al. 2001: 267ff; Palisade Corp. 2008; Bamberg and Baur 1989: 104ff; Morgan and Henrion 1990: 85ff)

Once the probability distribution functions have been determined for the uncertainty sources, they may be combined to provide uncertainty estimates for the entire calculation, model, or sub-model. If all the PDFs were normally distributed and independent, and all the relationships were additive, the overall standard deviation would be given by the formula:

$$S_{all} = \sqrt{{s_1}^2 + {s_2}^2 + \cdots + {s_n}^2} \tag{2.1}$$

Where:
S_{all} is the overall standard deviation,
S_i is the standard deviation of uncertainty source i, $i = 1 \dots n$

Where uncertain quantities are to be combined by multiplication, the combined uncertainty is more easily expressed as a percentage uncertainty (Hiraishi et al. 2000: 6.12):

$$U_{total} = \sqrt{{U_1}^2 + {U_2}^2 + \cdots + {U_n}^2} \tag{2.2}$$

Where:
U_{total} is the percentage uncertainty in the product of the quantities (half the 95% confidence interval divided by the total, i.e. the mean, and expressed as a percentage),
U_i are the percentage uncertainties associated with each of the quantities.

For a complex model and where possible, the application of a Monte Carlo simulation is recommended. This tool easily allows the use of all types of probability distribution functions and the inclusion of other than additive relationships. Furthermore, Monte Carlo analysis offers ready inclusion of correlation coefficients. (cf. Morgan and Henrion 1990: 183; Hiraishi et al. 2000: 6.18). In a Monte Carlo analysis, values from the probability distribution functions are chosen randomly and the original model is recalculated with these random numbers. The procedure is repeated many times, for example 10000 runs with random variables are completed with help of a computer. The distribution of the 10000 different results is the result of the Monte Carlo simulation. Many different statistical measures can be obtained of this distribution of results from the different iterations, for example: mean, standard deviation, skewness, kurtosis, and different confidence intervals. The standard deviation and 95% confidence interval are good measures for the uncertainty of the model – and shall therefore be used in the following.

So the methodology consists of six parts:

1. Identify the important steps in the underlying calculations
2. Develop probability distribution functions that express the uncertainty attached to each of these steps
3. Assess the relationship between the uncertainty of the different steps and use adequate linkages in the Monte Carlo simulation
4. Identify possible correlations between the uncertainty estimates for different steps
5. Run the Monte Carlo Simulation
6. Interpretation of results

2.2.3 Second order uncertainty – or dealing with the uncertainty of the uncertainty estimate

Quantifying the economic costs of climate change, a phenomenon that has only just begun, is a difficult task. It is no easier to come up with reliable figures about the standard deviation or the 95% confidence interval of existing cost estimates. A considerable amount of subjectivity in this process is inevitable. If anybody made the effort to calculate the uncertainty attached to this uncertainty estimate, the result would likely be rather large. However, the aim of this assessment is not to arrive at an accurate number but rather to help take uncertainty into account in integrated assessment models. It is interesting to see what the combined uncertainty would be, given the assumptions below about the uncertainties of the single steps. This is true even though the assumptions that necessarily have to be made are probably not everybody's assumptions, as long as they are clearly flagged.

To facilitate the interpretation of the results, a consistent method for the treatment of data and model insufficiencies is employed. In the following, a lower bound to true uncertainty is established. In other words: uncertainty shall be underestimated rather than overestimated, whenever an exact calculation is not possible. The consequence is, that the true uncertainty is at least as big as the result of the uncertainty model described in this thesis. It would also be interesting to know an upper limit to true uncertainty – but this is an even less tangible task than the lower bound.

This description of the task at hand implies an unusual definition of the word "conservative". In the following, the word "conservative" shall be used to describe that an assumption does not lead to an overestimate of uncertainty. The reverse conclusion is that "conservative" assumptions, as the word is used here, may imply an underestimate of uncertainty. This may appear counterintuitive in the beginning, but follows logically from the description of the aim of this thesis as given above.

2.3 Agriculture in FUND

Results from a lot of different researchers have been combined in FUND to an integrated assessment, and no single model exists anywhere that would reflect the whole process from the field study to the final cost estimate. Figure 2.1 shows the underlying models and structure of the representation of agriculture in FUND.

Tol (Tol 2002a,b; Tol and Heinzow 2003) has calculated the mean value for agricultural impacts from 6 underlying agricultural studies. In Figure 2.1 they can

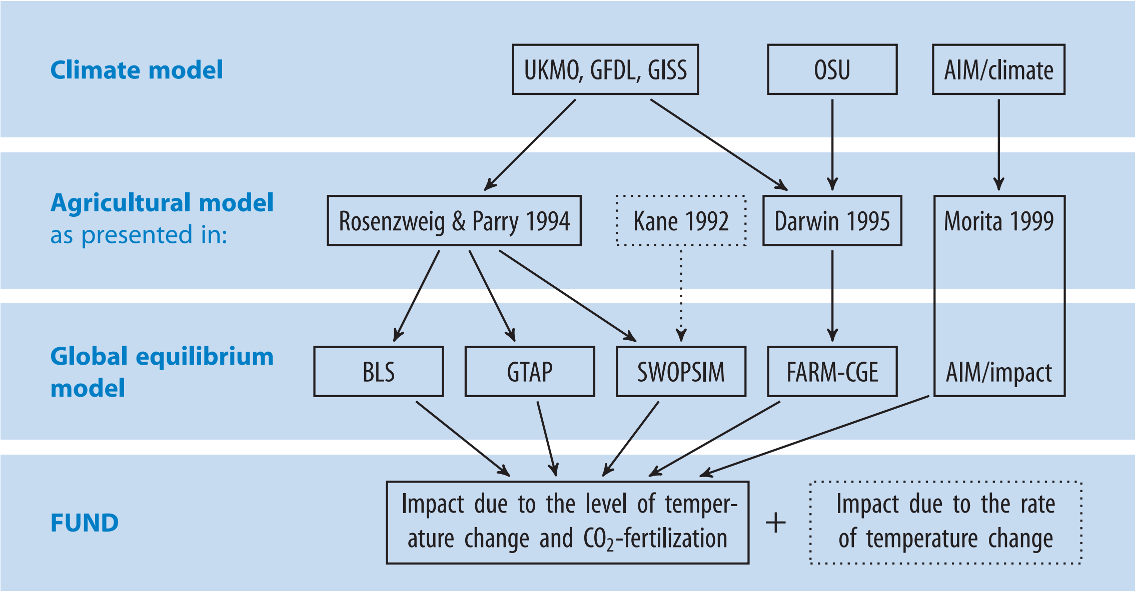

Figure 2.1: Input sources to the agricultural impact functions in FUND. (GFDL: Geophysical Fluid Dynamics Laboratory; GISS: Goddard Institute for Space Studies; UKMO: United Kingdom Meteorological Office; OSU: Oregon State University; BLS: Basic Linked System; GTAP: Global Trade Analysis Project; SWOPSIM: Static World Policy Simulation; AIM: Asia-Pacific Integrated Model; FARM-CGE: a computable general equilibrium model focusing on agricultural markets)

be identified as the three studies applying different global equilibrium models to the agricultural data from Rosenzweig and Parry (BLS, GTAP, SWOPSIM) and the three studies with independent agricultural estimates by Kane et al., Morita et al., and Darwin et al. Tol calculates results for the impacts caused by the level of climate change and the rate of climate change including CO_2-fertilization.

The boxes which are not regarded in the uncertainty analysis here are displayed with dashed borders. This is, first, the study by Kane et al. (1992). They work with a very simple modelling approach and regional breakdown (p. 25) based on climate data with very low regional resolution (p. 19f). And counter to newer evidence (e.g. Tubiello and Fischer 2007: 1045) the model predicts the highest losses for the US agriculture (p. 28f). Two of the three authors themselves turned to using the field data from Rosenzweig and Parry (1994) in a later study together with the same equilibrium model as before (Reilly et al. 1994: 27). This later study has been included in the uncertainty analysis presented in this thesis. For these reasons it is not assumed that the incorporation of the 1992 study by Kane et al. leads to a reduction of uncertainty. Furthermore, within the agricultural sector of FUND the focus of this thesis is on the impacts of the level of temperature change rather than the rate of change. According to Tol the impact due to the level of temperature change is a lot less speculative (Tol 2002b: 138), and thus a sounder basis for this uncertainty assessment with respect to the definition above of 'conservative'. It can be expected that the uncertainty of the more speculative impacts of the rate of temperature change is not smaller than the uncertainty of the impacts caused by the level of temperature change.

2.4 Adapted methodology to the special case at hand

The chain of calculations in IAMs is full of uncertainties (IEA Greenhouse Gas R&D Programme 1999: 7). In this thesis it is attempted to trace these uncertainties along the chain. As described above the calculations of FUND rely on the input of many other models, so it is not possible to effectuate a Monte Carlo analysis with an existing model. Due to lack of exact data and model formulas, it has neither been possible to model all the steps underlying the agricultural impact representation in FUND in exactly the same fashion as during the original calculations – including all climate-, crop- and trade models. A simplified model is developed with a focus on uncertainty only.

Therefore, the absolute value of the agricultural impacts is not regarded. Looking exclusively at the uncertainty of the estimate, a simpler model can be the basis of the Monte Carlo analysis. Consequently, not the mean value of the final result of the Monte Carlo analysis is of interest, but only the standard deviation as an indicator for uncertainty. A useful amount of information is available on the uncertainty of different scientific steps in the underlying models, which will be used here to quantify the approximate magnitude of the overall uncertainty within the chosen model structure.

A simpler model of the real models is constructed for the uncertainty analysis. For such a simpler model, it is necessary to represent the chain of calculations that led to the result for agricultural impacts. This is possible for the three studies that used the same agricultural data as published in Rosenzweig and Parry 1994. Therefore this concept is set to be the core of the following uncertainty analysis, as shown in figure 2.2. The influence of the studies by Darwin et al. and Morita et al. on the uncertainty assessment will be dealt with later in this thesis.

In FUND, the impacts for a 2.5°C warming are taken from the literature as well as some indicators for parameters of an impact function expanding the benchmark values to other levels of temperature rise. The simpler uncertainty model developed here focuses on impacts for the benchmark warming of 2.5°C. The uncertainty

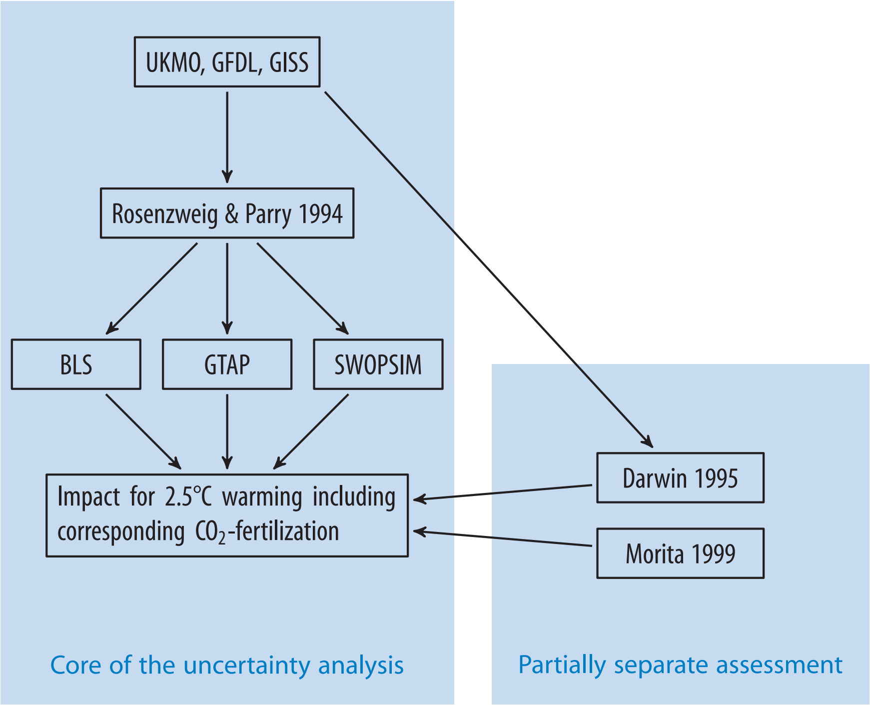

Figure 2.2: Reduced model structure for the uncertainty analysis

implications of the extension to other levels of warming are discussed further down.

The uncertainty estimate is effectuated for the global climate change impact results. FUND models several world regions separately, but it is not possible here to do a specific uncertainty analysis for every FUND region. Furthermore, the aim of this analysis is to gain some knowledge on the uncertainty of the climate cost estimate in FUND, and the knowledge gain from a regional analysis would be small compared to the general difficulties to derive a standard deviation of the cost estimate.

For the above-defined core of the uncertainty analysis it is possible to identify single, consecutive steps representing the impact assessment from the meteorological model to the final formula input in FUND. It is not necessary to reconstruct for example the meteorological model, but it is sufficient to deduce uncertainty information from the literature, develop a probability distribution function and treat the meteorological calculations as one step in the uncertainty assessment.

The arithmetic operator linking the probability distribution function of one step to the next depends on the logical relationship between them. For uncertainty analysis, multiplication is usually used. This reflects the case when it can be assumed that the error of the first step will be handed on, unchanged by the application of the next step – but that the error of the first step does have an influence on the following operations similar to compounded interest calculations in the banking sector.[1] This is a good approximation for the task at hand. Whenever more than a simple multiplication is logically necessary, this is described separately for the respective probability distribution functions.

For such a simplified representation of very complex calculations it is important to assure, that all probability distribution functions are calibrated to the same unit. Whereas in the original model inputs with a large variety of units were used and the outcome in the desired unit assured by the formulas applied, in the simplified model the calibration of all or most probability distribution functions to the same unit facilitates a realistic reconstruction of the linkages between the steps considerably. For the following uncertainty analysis the unit "% of total yields before climate change" will be used. So a standard deviation of, for example, 3% for one of the probability distribution functions would mean that with 68% probability the model is no more than 3% wrong on total yields due to the uncertainties underlying the calculations of this step. Furthermore, the probability distribution functions are normalized so that their mean value equals 100% of the final result. This is possible as only uncertainty is measured in this model. Therefore no relevant information is lost by the general setting of the means of the single probability distribution functions to the final result, which facilitates the evaluation of the model results. For a discussion of the difference of using yield before or after climate change as a calculation and calibration basis see chapter 2.10.

This definition enhances simplicity. Another possible metric would be "% of yield change caused by climate change". On the one hand, this would be closer to the subject of this uncertainty analysis. The research question is about the impacts of climate change and thus about the difference between future yields with and without climate change. On the other hand, this metric would be more difficult to handle, as it describes a percentage of an unknown quantity – the yield change caused by climate change. For many aspects of the analysis, uncertainty estimates are therefore not available in this metric. This would increase the problem of data availability, without delivering substantially more information or precision. Furthermore, even where data about yield change due to climate change is used, the available information is sometimes calibrated to represent a percentage of total yield, not a percentage of yield change. For example the data about the influence

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[1] To be on the safe side the calculations were repeated for an additive instead of a multiplicative model, and the results differed only marginally.

of different global circulation models is given in "% of total yield" (Rosenzweig and Parry 1994), referring to the uncertainty about climate change.

Data are not directly available in the unit chosen above for the development of probability distribution functions describing some relevant aspects of modelling climate change impacts. The treatment of these cases will be further elaborated in the descriptions of the concerned probability distribution functions. For example, knowledge about the uncertainty of total yield and knowledge about the uncertainty of yield change can be used in the same model whenever the units are handled with care. This calibration to "% of total yield before climate change" is used consistently throughout steps 1–7. Step 8 needs to be treated separately.

The probability distribution functions are developed based on a combination of statistical evaluation of different model results, expert opinion given by the original studies' authors themselves, up-to-date scientific knowledge published e.g. in the IPCC's Fourth Assessment Report (AR4, Easterling et al. 2007), and plausibility scrutiny. As Nordhaus (2007b: 75) pointed out, the use of judgemental probabilities is generally necessary in the analysis of climate change. Similarly the IPCC-guidelines recommend a pragmatic combination of available measured data and expert judgement if uncertainty ranges cannot be derived from source-specific measured data (Hiraishi et al. 2000: 6.5).

Furthermore, possible correlations between different probability distribution functions need to be identified and incorporated into the simulation. If, for example, a low value in one step of a multiplicative calculation increases the likelihood of a high value being realised in a different step, then the overall uncertainty is reduced. This can be integrated into the simulation via correlation factors.

Finally, the studies by Darwin et al. (1995) and Morita (IEA Greenhouse Gas R&D Programme 1999) need to be included separately. For the study by Darwin et al., only a minor part doesn't fit into the step-structure of the core chain of the uncertainty analysis. The probability distribution functions in the uncertainty model are therefore adapted suitably to represent the usage of the additional study by Darwin et al. in FUND. The study by Morita et al. is so different that it doesn't fit into the structure of the majority of the models used. A separate uncertainty assessment is reflected in the final result.

2.5 Identification of important steps

For the core of the uncertainty analysis eight separate steps contributing to uncertainty can be identified. These steps equally apply to all of the three studies using the same yield change data. The steps are:

1. Precipitation estimates
2. On-site crop growth models
3. Extrapolation from field studies to national yield changes
4. Extrapolation from national to global yield changes
5. CO_2 enrichment
6. Adaptation estimates at site level
7. Extrapolation of adaptation effects to the globe
8. Global equilibrium models

These steps describe the uncertainty attached to the production of the input variable to FUND, the economic impacts of a 2.5°C warming and the corresponding increase in the atmospheric CO_2-concentration. Further uncertainty can be introduced by the calculations in the FUND model itself, an issue that will be considered separately.

2.6 Development of the probability distribution functions

2.6.1 General approaches and methodology

Various possibilities exist to derive probability distribution functions for the uncertainty analysis:

(a) Several independent studies are available:

When several largely independent study results are available for the same step, they are treated as independent realizations of an underlying probability distribution function. The standard deviation of the probability distribution function used for the uncertainty calculation in this thesis is then calculated as follows:

First the variance of the original study results is estimated via the common formula:

$$s^2 := \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu)^2 \tag{2.3}$$

where μ is the sample mean,
x_i are the individual study results, and
n is the number of independent studies.

Then the likely standard deviation of the estimator of the mean is derived:

$$s\bar{x} = \sqrt{\frac{s^2}{n}} \tag{2.4}$$

This standard deviation quantifies the effect that the correct value can not be obtained with a (very) limited number of study observations. It is the standard deviation of the probability distribution functions used in the calculations of this thesis. Actually this calculation procedure may be a severe underestimation of the true uncertainty if the available study results are already based on mean values and are thus representing only a minor part of the real uncertainty (cf. Hoogenboom 2006: 102). This procedure is used to make sure the uncertainty is not overestimated.

(b) Upper and lower bounds are known:
When upper and lower bounds to the uncertainty distribution are known from the literature, a triangular probability distribution function bounded by these figures is used. Unless other information is available, the triangular PDF is assumed to be symmetric. Wherever possible, the best guess value is derived from quantitative or qualitative knowledge in the literature.

(c) Scarce data basis:
Where the objective data basis for the uncertainty analysis is scarce, plausibility considerations, general current knowledge about the effects of climate change on agriculture and comments by the study authors themselves are used as additional input for the development of a suitable probability distribution function. Conservative estimates are employed. Thus uncertainty is rather underestimated than overestimated. Actually the results are probably an underestimate of the true uncertainty for three more reasons: First, structural uncertainty, i.e. the question to which extent the combination of the single steps is not a perfect representation of reality, is not assessed in this paper (cf. Asselt, Rotmans, et al. 1995: 11). Second, there may be contributions to climate change amplifying uncertainty about which nobody has thought so far, especially as climate change has very long-term consequences on a complex system. Third, it is expected that some uncertain amplifying feedback mechanisms exist which are not fully incorporated into the models, e.g. methane leakages from permafrost (Flessa et al. 2008), carbon emissions from soils (Bauer et al. 2006: 419) or N_2O-emissions from tropical soils (Veldkamp 2008).

2.6.2 Development of probability distribution functions for the core uncertainty analysis

Step 1 – Precipitation estimates

Climate Change projections are fraught with uncertainty in regard to both the rate and magnitude of temperature and precipitation alterations in coming decades (Rosenzweig and Hillel 2005a: 245). Rosenzweig and Parry (1994) calculate yield changes for three global circulation models (GCMs). These three models lead to substantially different yield changes for the same change in CO_2-concentration. The results are given in a graphical format with different colours indicating different percentages of yield change. Numerical results are not given. In order to be able to work with the results, they are transformed into numbers, assuming that the appropriate value for every FUND region is the central point of the range that the respective colour indicates. Percent yield changes are then multiplied by the region's agricultural product, and the results for all regions are added to arrive at numbers for global yield change. Using the central value of every colour as the appropriate basis for further calculations is deemed to be acceptable considering the uncertainties involved. Possibly the authors didn't give the exact numbers on purpose, to avoid the appearance of a certainty that does not exist. At the global level, the three GCMs predict yield changes of −15%, −22%, and −30% without adaptation and without CO_2-fertilization. As the difference between these results is not likely to be significantly affected by the identical further treatment of the climate data in the model, it can be assumed that the variation is an indicator of the uncertainty introduced by incomplete knowledge about future climate, not any other factor as for example plant growth.

Two factors mainly account for these differences in yields with climate change: different temperature predictions and different precipitation predictions. The effect of varying temperature assumptions, on the one hand, is of no direct interest here as Tol standardises the results to a temperature change of 2.5°C. His aim in the process is to assess yield changes for a certain warming, so the amount of global warming for a given greenhouse gas concentration cannot be regarded as an uncertain input parameter. There are two reasons, however, why differing temperature predictions can contribute to overall uncertainty. First, there is no perfect knowledge of the relationship between yield changes and different temperatures. Uncertainty is introduced by the conversion of results from the three GCMs mentioned above to 2.5°C. Three GCMs expected higher levels of warming for a doubling of the CO_2-concentration. A general discussion of the opposite process – extrapolating Tol's

2.5°C results to higher temperatures, will be given further down. Second, different global circulation models predicting similar overall temperature changes can still disagree fundamentally on regional temperature developments (IEA Greenhouse Gas R&D Programme 1999: 4). However, to remain on the conservative side, these aspects are not considered here.

On the other hand, lack of knowledge about the development of precipitation patterns for a certain amount of warming certainly contributes to the uncertainty measured here. Therefore, this uncertainty is a necessary input to the uncertainty model developed here. The uncertainty connected to precipitation can be identified, when the amount of disagreement on yield changes connected to different climate models is split up into the contributions of the two factors, temperature and precipitation. Such an identification of the contributions of temperature and precipitation to the uncertainty of the GCMs is attempted in the following.

The change in average temperature varies between the three GCMs by 23% of the maximum predicted change; the change in global precipitation varies by 50% of the biggest predicted change. At the local level, precipitation is probably even more difficult to project compared to temperature (see IEA Greenhouse Gas R&D Programme 1999: 10). The large uncertainty concerning soil moisture and precipitation was confirmed and emphasized by Rosenzweig et al. (1993: 4) (cf. Betz 2005: 83; Tubiello and Fischer 2007: 1036), and the very wide disparity in regional water runoff predictions of the GCMs mentioned above as given in Darwin et al. (1995: table 16, see also page 20) clearly supports this assumption: The disparities between the models even at continental scale for most regions are about the size of the global precipitation change, a lot more than that for Australia and New Zealand. Table S2 in IEA Greenhouse Gas R&D Programme (1999) further illustrates the uncertainty of regional precipitation predictions. Regional climate models that reflect the real world in a lot more detail than those used in Rosenzweig et al. (1993: 2) were shown not to predict precipitation significantly better either (Takle and Pan 2005: 393). Even the atmospheric processes involving aerosols which are a precursor of precipitation are highly uncertain (Pöschl 2005: 7535). Thus, following the assumption by Rosenzweig and Hillel (1998: 141) and Bates et al. (2008: 59) that temperature change does not have a considerably larger effect on yield changes than precipitation change, two thirds of the yield result differences caused by the different climate models are attributed to the factor precipitation.

As described above the standard deviation of the estimator-PDF is calculated with help of the formulas 2.3 and 2.4 (p. 40f) for each of the regions. The results are then multiplied by 2/3 to account only for the effect of precipitation. The regional numbers are weighted by the percentage of global agricultural product and the weighted average is used for the global probability distribution function of step 1. The result is a standard deviation of 3.1%. A normal distribution is assumed. There doesn't seem to be a plausible reason to assume a non-symmetrical distribution. Over- and underestimates of yield due to errors in precipitation assumption seem equally plausible, at least where precipitation changes no higher than 50% are involved. Such extreme changes don't seem to be expected in the climate warming range considered here (Darwin et al. 1995: table 16).

The following numerical example illustrates the meaning of the standard deviation calculated above in the context here: A normal distribution with a standard deviation of 3.1% means that if for example the yield change has a mean value of –20%, the 95% confidence interval due to uncertainty in the precipitation estimates is about two times the standard deviation of 3.1% of total yield, that is –13.8% to –26.2%.

The standard deviation is higher looking at regional instead of global results. The three GCMs differ by as much as "0% to –10%" yield change predicted for Canada in GISS and "–30% to –50%" in UKMO without fertilization, or for Eastern Europe GISS reports "+10% to 0%" compared to a predicted change of "–20% to –30%" in UKMO. Only the regions Central America and Australia/New Zealand end up in the same range of predicted yield change for all three GCMs. These regions together are responsible for only 3.2% of global agricultural product. And at least for Australia the agreement between models seems to be the result of different underlying assumptions leading to the same result by chance, as the water runoff predictions for the regions vary widely between the GCMs (Darwin et al. 1995: table 16).

The scenarios with adaptation are less relevant for this comparison due to the assumptions made in the study by Rosenzweig and Parry. There, it is assumed that adaptation can only offset half or all of the losses, but not increase gains. This assumption acts like a convergence factor in most regions, moving large parts of the world close to zero change. Furthermore adaptation estimates were not calculated for all sites. Therefore the figures without adaptation are used here to identify the uncertainty attached to the GCMs in question, but the effect of adaptation on uncertainty is assessed separately further down.

Several features suggest that the real uncertainty is actually larger. The climate models use best guess values instead of the whole spectrum of possible outcomes, and the three GCMs are hardly completely independent. For example none of the models include change in water runoff due to changes in snowpack and glaciers

(Darwin et al. 1995: 21). There are very probably more similarities in the model structures that cannot be ascribed to reality. Furthermore the effects of increasing weather variability opposed to changing average precipitation and temperatures are not included, although the former is today thought to be the more important effect (Parry et al. 2007: 299; Rosenzweig and Hillel 2005a: 264; Takle and Pan 2005: 392). On the other hand the yield differences between the models were calculated for 4°C, 4.2°C and 5.2°C above pre-industrial temperatures. It can be expected that uncertainty for this range of warming is considerably larger than at 2.5°C. This issue will be dealt with in detail further down as it could be relevant for all steps.

Step 2 – 112 on-site crop growth models

Rosenzweig and Parry (1994) used the IBSNAT models (International Benchmark Sites Network for Agrotechnology Transfer; CERES-Wheat, CERES-Maize, CERES-Rice and SOYGRO are the four dynamic crop growth models developed by the US Agency for International Development) to estimate yields at 112 sites. Real-life conditions often differ from experimental ones and the exact timing of heat or water stress has a very important but difficult to predict influence on yield results (Takle and Pan 2005: 385, 392f). Rosenzweig et al. (1993: 6) write in their description of the model:

> The crop models embody a number of simplifications. For example, weeds, diseases, and insect pests are assumed to be controlled; there are no problem soil conditions (e.g. salinity or acidity); and there are no extreme weather events such as tornadoes. The models are calibrated to experimental field data which often have yields higher than those currently typical under farming conditions.

Otter-Nacke et al. (1986) is the most comprehensive research on evaluation of CERES-Wheat. For the version without regard to nitrogen-limitations, they found a mean absolute error of 22% of mean observed yield (p.19). For CERES-Wheat-N with nitrogen limitation no truly independent data sets were available for validation (p. 28). Due to this lack of independence the results should rather underestimate than overestimate the error. It was shown that with 95% probability the simulated yield could be predicted with an error no bigger than 47% of the mean observed yield (p. 32 and table 8 on p. 40). Assuming a normal distribution this would correspond to a standard deviation for the probability distribution function of uncertainty for step 2 of 23%. Landau et al. (1998: 91) show results where simulations differ by roughly 40% from observed yields for England in the past.

For the CERES-Maize model, Du Toit et al. (1999) found a low simulation accuracy ($r^2 = 0.0001$), but report that another study by Thornton et al. (1995) found a very good match between simulation and measurement ($r^3 = 0.94$), whereas Mbabaliye and Wojtkowski (1994) found r^2 to be 0.1. Travasso and Magrin (1998: table 2) tested the CERES-Barley model and found a root mean square error of 11.7% of mean yield. He claims this is a good performance for a crop model (p. 333), which is confirmed by the findings from other models above. For various wheat-models, O'Leary (1999: figure 1) equally found that only 1 of 11 results had a root mean square error of less than 10% of simulated mean yield, and that one only slightly less. Almost half of the results have a mean square error around 20% of simulated yield.

For step 2 the difficulty arises, that available data is for the difference between measured yield today and modeled yield today, not for a world with climate change. Figure 2.3 illustrates the relationship between the two concepts.

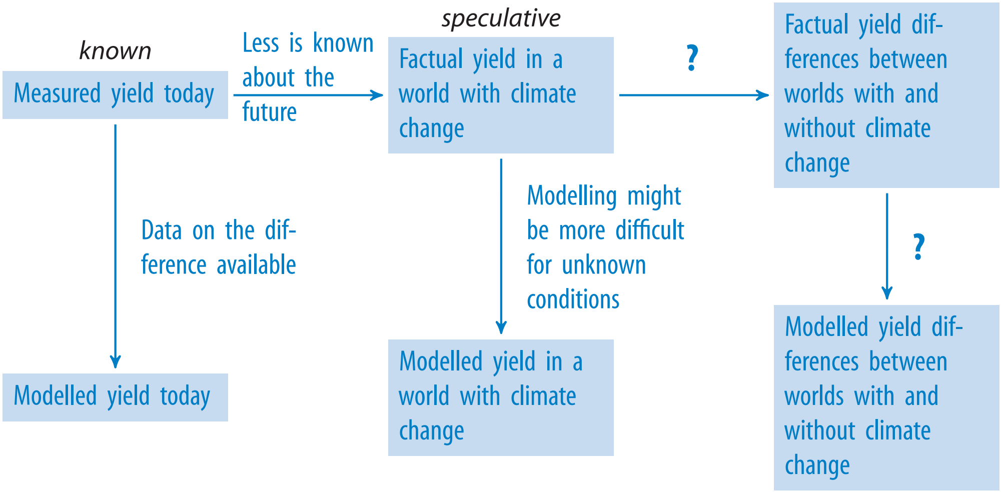

Figure 2.3: Relationship between available information and necessary information, own graph

As figure 2.3 describes, there is no straightforward formula for the relationship between the necessary information about the difference between modelled and factual yield changes due to climate change on the one hand, and the available information about the performance of the yield models for current yields. To remain on the conservative side, it is necessary to show that uncertainty indicated by the arrows for the two boxes on the right is not smaller than the uncertainty of the two boxes on the left. Two reasons can be named in favour of this assumption:

First, it is likely that the crop models are rather less than more correct when predictions need to be made about the future world with unknown conditions. Second, the necessary information about the impacts of climate change in the future involves the comparison of two unknown figures: modelled future yield without climate change and modelled yield with climate change. In the comparison between measured yield today and modelled yield today only one figure is unknown.

On the other hand, some of the errors of the yield model might apply equally to the calculation for the yields with and without climate change – and part of the errors would thus cancel each other out. But as the detailed analysis of the CERES-wheat model by Otter-Nacke et al. (1986: figure 2) shows, yields are sometimes overestimated and sometimes underestimated. It is therefore easily possible, that errors do not cancel each other out. To be on the safe side, the standard deviation of the probability distribution function is reduced by one third. This applies equally to the steps 3 and 4.

The most extensive study by Otter-Nacke et al. indicates an appropriate standard deviation of 23%. As a few studies named above suggest a lower uncertainty, a standard deviation of 15% is used. The further reduction by one third leads to the use of a standard deviation of 10%. A normal distribution is assumed. Again there doesn’t seem to be a reason to use any other than a symmetrical probability distribution function. The probability of a 100% yield loss, which is indeed an asymmetrical and natural boundary to the probability distribution function, is so small, that it can be neglected for the purpose of this thesis. The same is true for the probability distribution functions of the following steps.

Uncertainty is further increased by the fact that plant growth under future, not-yet existing conditions is not easy to estimate. Agriculture itself has an important feedback effect on local climatic conditions (Takle and Pan 2005: 399) which was not included in the yield models. To remain on the conservative side, this effect is not regarded here.

Step 3 – Extrapolation from field studies to national yield changes

Steps 3 and 4 are the biggest source of uncertainty according to Rosenzweig et al.:

> The primary sources of uncertainty lie in the sparseness of the crop modelling sites and the lack of explicitly modelled yield changes in subsistence crops such as millet and cassava. (Rosenzweig and Parry 1994: 134)

In step 3, the uncertainty of deducing national yield changes from on average 6 site specific results per nation (112 sites in 18 countries) is estimated. In the study reported by Rosenzweig et al., these crop yield changes were calculated employing yield transfer functions. With these formulae, yield estimates from a study site are transferred to other fields in the same nation. Parameters that enter the calculation are for example soil conditions and precipitation patterns. The correlations between simulated crop yields and yields derived from the transfer functions were over 70% (Parry et al. 2004: 54). For the following calculation it is assumed that in general the gap between model and reality is very unlikely to be substantially bigger than found in this comparison. It is therefore assumed that with 95% probability the results from the transfer function are no more than 30% wrong. This leads to a standard deviation of 15% for the probability distribution function of step 3. The reduction by one third in analogy to the considerations outlined for step 2 leads to a standard deviation of 10%.

Plausibility check of steps 1–3 relying on an independent source

Takle and Pan (2005: 394) compared model yield results from coupling a regional climate model with a crop growing model for a district in North Iowa to measured yields over the ten year period 1979–1988. Observed yields were 8381 kg/ha, whereas simulated yields were 5487 kg/ha, with a considerable higher annual variability in the model than in reality. In the following the uncertainty information from Takle and Pan is compared to the uncertainty estimate of the model developed here. For this purpose, the compound uncertainty of steps one to three as described above is calculated. The standard deviation of step one is 3.1%, of step two and step three 10% each. The compound standard deviation of steps one to three is 14.5% of total yield, whereas the difference between observed and simulated yields reported by Takle and Pan is 35% of total yields. For the combined probability distribution function of steps 1–3, such an error of 35% or bigger does not occur with a probability of 98.3%. Figure 2.4 illustrates this: The combined probability

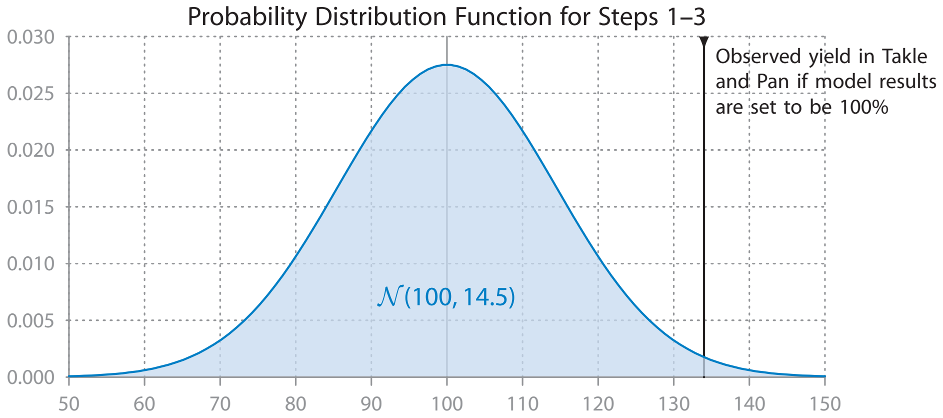

Figure 2.4: Comparison of the probability distribution function for steps 1–3 with the difference between model results and reality in Takle and Pan, own graph

distribution function of steps 1 to 3 includes extrapolation to the national level, the comparison by Takle and Pan only to the district level. So steps 1–3 include a wider range of uncertainties. Furthermore, the results from Takle and Pan are newer, and Otter-Nacke et al. (1986: 27) pointed out that a regional model could easily be more exact than the global CERES models. And the model experiment described by Takle and Pan is for current climate conditions. It can be assumed that they are more easily represented in a model than climate conditions in a future, unknown world. In a different model run, Takle and Pan used climate data from a future scenario downscaled to the regional level. Total yield under future conditions was estimated to be 10610 kg/ha, whereas current climate data from the same global model downscaled to the region led to a result of 5002 kg/ha. This shows that the difference between yields under current and future climate conditions can be very substantial. The difficulty to model future yield changes with the help of models that were calibrated to current empirical data is therefore relevant.

On the other hand, the standard deviation for steps one to three was designed to exclude the uncertainty of how much temperatures (not precipitation) will change for a doubling of CO_2 in the atmosphere, whereas uncertain temperature is included in the results by Takle and Pan. Furthermore the results in Rosenzweig et al. are based on average results from three different global circulation models, which may reduce the bias. But on the whole and taking into account that the difference between actual and modelled yields reported in Takle and Pan is two and a half times our assumed standard deviation, their results are a strong indication that the combined uncertainty for steps one to three was not overestimated.

Indicators, that the uncertainty in the study from Takle and Pan may be smaller	Indicators, that the uncertainty in this thesis may be smaller
• regional crop growth model better adapted to local conditions than a global crop growth model • regional level easier to handle than the national level • current climate conditions easier to handle than the future	• in this thesis, the influence of temperature is not included as the estimate is defined to be for a 2.5°C warming • average result based on 3 global circulation models may perform better

Table 2.1: Overview of different contributions to uncertainty in Takle & Pan (2005), and the analysis here

In table 2.1 it is assessed whether the uncertainty in the study from Takle and Pan is likely to be smaller or bigger than in the models represented in the uncertainty model developed in this thesis. The assessment is qualitative and the indicators for both sides are given in the table.

Step 4 – Extrapolation from national to global yield changes

Step 4 represents the uncertainty of deducing global results from 18 national estimates. It is reasonable to assume that this is not easier than the extrapolation in step 3, especially as not all crop types were included in the modelling and the effects of climate change on other crops may be substantially different. This difficulty was not included in the uncertainty assessment of step 3. In the study from Rosenzweig et al., wheat, rice, corn and soy beans were simulated. The first three contribute 85% to world cereal exports (Parry et al. 2004: 54), but the contribution to world food production is smaller as subsistence crops are rarely exported. As no direct data for the uncertainty of this step was available, a standard deviation 25% smaller than in step 3 is assumed. This is almost certainly a conservative estimate. Therefore, the standard deviation is 7.5%.

Step 5 – CO_2 enrichment

When the CO_2-concentration in the atmosphere increases, plant growth will probably be enhanced as CO_2 is an important input to plant growth. This effect is called CO_2 enrichment or CO_2-fertilization. The magnitude of this effect depends both on the plant species and on other external conditions as water and nutrient availability and climate conditions.

Results are adapted for CO_2-fertilization before they are used as an input to the FUND-model. It might be argued, that CO_2-fertilization should logically be step 3 rather than step 5. This is not a very important question, as the sequence in this case has no influence on the final result. The decision for CO_2-enrichment as step 5 is based on the description of the modelling work by Rosenzweig and Parry as well as by Richard Tol. As not all the underlying studies of the agricultural sector of FUND incorporate CO_2-fertilization, Tol adapted the results for this phenomenon afterwards (Tol 2002a: 52). The same is true for adaptation.

The authors (Rosenzweig and Parry 1994: 134) state that their results with fertilization may have a positive bias, as laboratory results probably overestimate the real effect. Yield increases may be reduced by high tropospheric ozone concentrations, which are predicted under climate change scenarios, and CO_2-fertilization could lead to declining food quality (Warren et al. 2006a: 36). On the other hand, no fertilization would probably introduce a negative bias, as some is likely to occur. In this case the results with and without CO_2-fertilization are assumed to be upper and lower bounds to uncertainty (also assumed in Parry et al. 2004: 64; cf. Bates et al. 2008: 60), represented by a symmetric triangular probability density function. As the results with and without CO_2-fertilization differ by 18.4% on average, a triangular PDF with $\mu = 1$, lowest possible value −8.2% and highest possible value 10.2% represents this range of uncertainty correctly. The level of the CO_2 concentration in the atmosphere for a 2.5°C warming is also highly uncertain (IPCC 2007b: 12), but this uncertainty is not included here. Thus our uncertainty estimate is an underestimate of the true uncertainty.

Step 6 – Adaptation estimates at site level

The authors themselves elaborate why adaptation is difficult to predict (Rosenzweig and Parry 1994: 135). Rosenzweig et al. (1993: 9) describe knowledge on adaptation in their model as follows:

> The adaptation simulations were not comprehensive because all possible combinations of farmer responses were not tested at every site. Spatial analyses of crop, climatic, and soil resources are needed to test fully the possibilities for crop substitution. Neither the availability of water supplies for irrigation nor the costs of adaptation were considered in this study; these are both critical needs for further research.

For the development of a plausible probability distribution function, two aspects are important: On the one hand, knowledge about the effectiveness of adaptation is still highly uncertain (see also Easterling et al. 2007: 295; European Environmental

Agency 2007: 32). On the other hand, the influence of adaptation on the final result measured in percent of total yield is not such an important contribution, as adaptation changes will usually be a fraction of, or about the magnitude of the absolute yield changes without adaptation. Assuming a mean value between impacts with and without CO_2-fertilization in accordance with the assumptions under step 5, Rosenzweig and Parry (1994) predict a mean global yield change of –13% (average of all three climate models used). Theoretically, different adaptation influences in this same range are conceivable: It is likely, that some negative impacts can be offset through adaptation. But adaptation can also lead to gains, not only offset damages. However, for temperature changes beyond 1–2°C, it is not expected that losses can be turned into gains on average (Easterling et al. 2007: 275). So the possible range of possible adaptation results is about as large as the impact, but the extreme ends are less likely than an intermediate value. Therefore a triangular probability distribution function is used. It is bounded by the two extremes: very little adaptation possible – adaptation leads to gains larger than the negative impacts of climate change. In order to remain on the conservative side, only 10% is used as the width of the triangular function, saying that an error of no bigger than 5% of global yield in either direction is included as a possibility.

Step 7 – Extrapolation of adaptation effects to the globe

Rather crude assumptions have been made in the underlying study: for all world regions adaptation cancels either 50% or 100% or none of the damages without adaptation, depending on the results from field studies at some of the study sites. Gains are excluded. Here it is assumed that all countries are in the category that best reflects reality, but that the real value may be anywhere between 0 and 25%, between 25 and 75% or between 75 and 125% of yield change predicted. The average magnitude of these three intervals is 40% of yield change, which Rosenzweig and Parry estimated to be –13%. Therefore a monotone distribution function with the width 5% of global yield is used. This is an underestimate of true uncertainty as it is very unlikely that all regions are in the adaptation category (none, half or all damages avoided) that best reflects the future reality. Furthermore, countries may switch from one category to another for different levels of global warming (cf. Easterling et al. 2007: 275).

Step 8 – Global equilibrium models

Step eight representing the uncertainty introduced by the usage of a global equilibrium model is the only step in our simulation with a different metric. Results are not logically represented in percent of yield change, but in percent of welfare change, where welfare is defined as the sum of producer surplus and consumer surplus.

The uncertainty introduced by step 8 depends crucially on whether it is assessed from the global or from the regional perspective. From a global point of view, gains and losses in different regions can be expected to partially offset each other. Thus global yield changes are smaller than regional yield changes, and consequently errors in the calculation of regional yield changes. If this implies that errors from different regions also partially offset each other, uncertainty is reduced. The second assumption does not necessarily follow from the first. A small example can show this: Let's assume 3 regions of equal size, each with a production before climate change of 10 units of food. Climate change leads to a change in production of −3 units for region A, +4 units for region B, and −2 units for region C. Yield changes are therefore in the range of 20 to 40% of absolute yield. For all three regions together climate change consequently causes a loss of 1 unit out of 30, that is 3.3% of total production. If it is assumed that, due to an error in the yield model, production after climate change is generally underestimated by 10%, predicting −4 units for region A, +3 units for region B, and −3 units for regions C. The model thus predicts a global yield change of 4 units out of 30. The error of the model result compared to the real yield change is exactly 3 units out of 30 or 10%. Thus the errors in the single regions are fully reflected in the global result, although the yield change on the global level is clearly smaller than the yield changes in each of the regions.

However, for a conservative estimate of uncertainty in the sense of not overestimating uncertainty other combinations should be regarded as well. On the one hand, the possibility of regional errors partially offsetting each other should be taken into account. In general, global trade is expected to buffer supply and price fluctuations (Downing 2003: 93; Easterling et al. 2007: 284). To a certain extent this applies also to regional impacts: errors in different sub-regions may partially offset each other. On the other hand, decreasing competitiveness in a global market may lead to decreasing exports or increasing imports, and thus further reduce the domestic agricultural product compared to a world without climate change, and vice versa. Thus regional yield changes can be expected to be intensified due to international trade. In the following, neither an increase nor a decrease of welfare effects through global trade is adopted. This is warranted as Tol gives regional results in his studies.

Another important aspect was explained by both Cline (2007: 32f) and the IPCC's Second Assessment Report (Pearce et al. 1996: 186): in the agricultural sector welfare changes are always bigger than yield losses, and more so for bigger yield losses. In the case of food, the demand is very inelastic and rising prices lead to quickly diminishing consumer surplus.

Furthermore the global equilibrium models themselves introduce a range of uncertainties, which are assessed in the following. From the three equilibrium models applied to the data of Rosenzweig and Parry, only two give results in the same metric, welfare change: Tsigas et al. (1997) with the GTAP model (global trade analysis project) and Reilly et al. (1994) with the SWOPSIM (Static World Policy Simulation) model. For the BLS (Basic Linked System, Rosenzweig and Parry (1994)) only production and price changes are reported, which can't be converted into welfare changes without more knowledge about the model. So unfortunately only two models are available for comparison. Tsigas et al. (1997) gives results from GTAP for two partial and one general equilibrium model, SWOPSIM is a partial equilibrium model. In order to assure comparability, from GTAP the partial equilibrium model most closely similar to SWOPSIM has been chosen, the version PE1. However, it must be noted, that the sectors allowed to adjust to the new equilibrium do not match perfectly with those in SWOPSIM. The difference between the results of these two models measured at million $ welfare change are 25% of the yield change predicted in Rosenzweig and Parry, if these are valued at 1995 prices.

Gehlhar (1997) tested the accuracy of the GTAP model, comparing model results to real world data in a backcasting exercise. Without further improvements, GTAP was only able to predict 18% of the change that took place in the real world (p. 359f). Thus the limitations of general equilibrium models become obvious. Moreover, SWOPSIM has no socio-economic scenario and contrary to reality assumes that the effects of climate change hit an economy equal to the one from 1987 (Reilly et al. 1994: 27). Tsigas et al. (1997) don't explore the consequences of various socio-economic scenarios either. But as Easterling et al. (2007: 298) pointed out, impacts on food security will depend strongly on the socio-economic development. It can be expected that prices will be affected as well. Furthermore, future competing demand for freshwater from domestic and commercial users is also influenced by socio-economic developments (Rosenzweig and Hillel 2005a: 256).

The results from Gehlhar (1997: 359f) and the other shortcomings of the equilibrium models outlined above suggest that considerable uncertainty might be introduced by the application of general equilibrium models. But this uncertainty of step 8 is even more difficult to calculate than those of the previous steps because as explained above step 8 has a different metric and the data availability is very limited. An overestimate of uncertainty shall be avoided and therefore step 8 is not included in the calculation of the conservative uncertainty estimate.

2.7 Modelling of the relationship between different steps in the Monte Carlo simulation

It is important to correctly reproduce the model structure, i.e. the relationship between the 8 steps. Step 1 in our simulation has been defined in a way to assure a multiplicative relationship to step 2. The question answered by the probability distribution function is: an error of how many percent of yield in either direction will not be exceeded with a 68% probability (standard deviation) due to uncertainty about local precipitation. So if, for example, the simulation picks a value that represents an error of 3%, the error would still be 3% after conducting the 118 field studies, if there were no further error introduced in that process. If step two introduces an error, its size is likely affected by the error in step one. Similarly, steps two and three have a multiplicative relationship: a certain error coming out of the field study would most likely be reproduced in the aggregation to national results. The same is true for the aggregation of 12 national results to the globe. Therefore the linkages of these steps are simple multiplications in the Monte Carlo analysis.

Step five, CO_2-fertilization, is a positive shift of the yield change result with unknown magnitude. The mean of the calculation will certainly increase, but the mean is not assessed here and therefore this feature can be disregarded. The standard deviation has again a multiplicative relationship to the previous steps and is linked with a multiplication in the Monte Carlo analysis.

Step six is adaptation at the field study level. During the development of the results by Rosenzweig and Parry, step six was not linearly integrated between step five and step seven. Rather, step six was developed as an additional side information, which was incorporated into the model via step seven. Figure 2.5 displays this structure, which can be reproduced in the simplified analysis model for the uncertainty assessment. However, as all the steps are linked via multiplication,

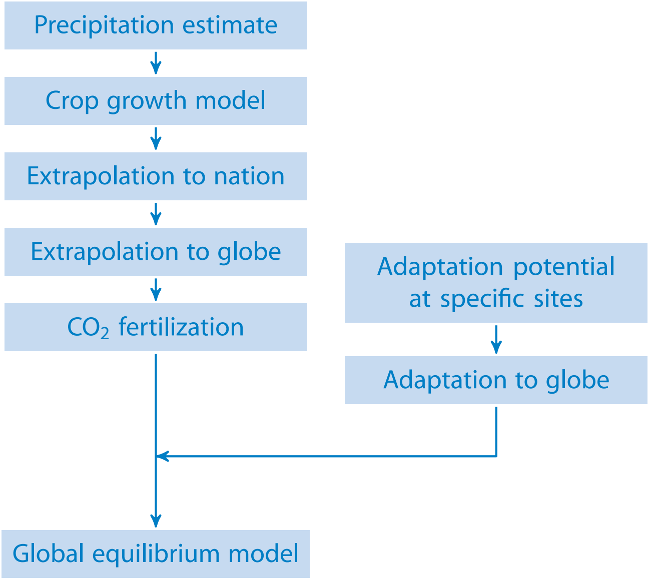

Figure 2.5: Structure of the work by Rosenzweig and Parry

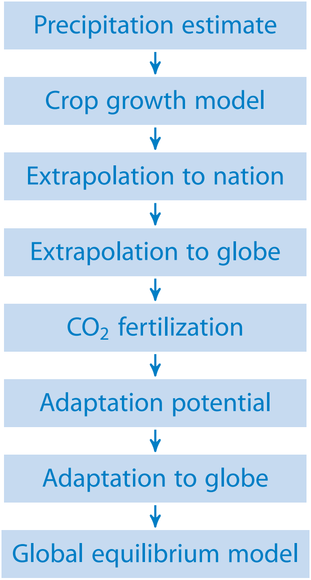

Figure 2.6: Simplified structure

the result is not affected by this structure compared to a linear representation as in Figure 2.6. For the sake of simplicity the linear structure is used.[2]

Step six has another important specialty: Through adaptation, all negative yield changes are being reduced, no matter how big they are. Correspondingly, the uncertainty is reduced proportionally. If, for example, before adaptation it was uncertain whether 10% or 20% of total yield are lost because of climate change, a 40% reduction of losses through adaptation would mean that between 6% and 12% of total yields are lost. So, where the range of possible yield reductions was 10% of total yield before taking into account adaptation, it is just 6% of total yield after the consideration of adaptation. The uncertainty is equally reduced by 40%.

Naturally, this effect needs to be reflected in the simplified model for the purpose of the uncertainty calculation. Two considerations are necessary:

First, information is needed about the percentage of losses that can be avoided through adaptation. Although this section deals with the relationships of the different steps to each other, information about the relative magnitude of adaptation compared to the losses through climate change is needed here. That is, not only information about uncertainty, but also about the magnitude of the losses is needed as an input to correctly describe the relationship of the different probability distribution functions. The scope of adaptation was also discussed above where the

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[2] The model with the structure as in figure 2.5 was also built and tested, but with no discernible difference in the results.

standard deviations for the probability distribution functions involving adaptation were developed. In the following the discussion is continued with a focus on the aspects relevant for the determination of the relationship of the probability distribution functions developed above.

Increased gains through adaptation are disregarded for the sake of simplicity here. They would increase the standard deviation. It is thus in line with this thesis' definition of "conservative" estimate to exclude them from the assessment of the effects of adaptation on total yield change. Even with this simplification, it is difficult to predict which proportion of damages will be avoided through adaptation. A range of barriers for adaptation exists. In the past, droughts in the African Sahel region have shown physical limits to adapting to new climate conditions; in different parts of the world, financial resources restrict farmers' capacities to adapt (Adger et al. 2007: 734). Furthermore multiple stresses reduce the possibilities for adaptation. For example water scarcity is a problem for other reasons than climate change while water use has doubled over the last four decades (Yohe et al. 2007: 816). This limits the scope for irrigation. The likely percentage of yield losses prevented through adaptation is further reduced by cognitive and cultural barriers (Adger et al. 2007: 735f; Easterling et al. 2007: 295). The IPCC's Fourth Assessment Report states that warming above 1.5–3°C in the tropics and 4.5–5°C in temperate regions exceeds adaptive capacity (Easterling et al. 2007: 295). Many models either overestimate or underestimate the scope of adaptation (Lorenzoni and Adger 2006: 73). From this follows, that the effect of adaptation is notably bigger than zero and notably smaller than offsetting all damages.

To reflect this uncertainty, a probability distribution function is used to describe the portion of damages avoided through adaptation. And to remain on the conservative side, more than half of the damages are assumed to be most likely avoided through adaptation: a triangular function with most likely value 60%, 40% as the lower bound and 80% as the upper bound is used. Figure 2.7 illustrates this assumption graphically: The bars on the left portray a random difference in total yield with and without climate change and without adaptation. The triangle is then the probability distribution function determining the probability of different yield results after adaptation. The two bars on the right once again illustrate the yield difference without climate change versus with climate change and adaptation. Values anywhere on the height of the triangle are possible, with the most likely value at its peak. The triangle is probably rather small, taking into account all the imponderables named above. This again enhances the conservative character of

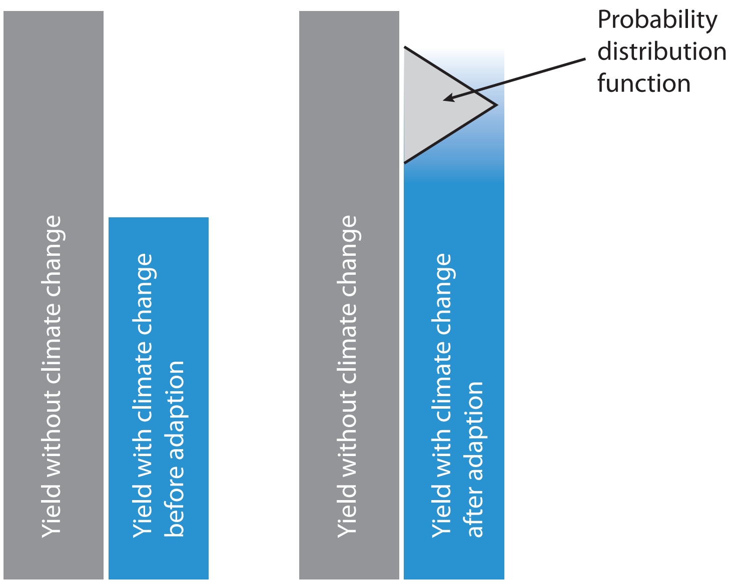

Figure 2.7: Assumption about proportion of yield losses avoided through adaptation

the calculation. A broader triangle with the same peak would increase the standard deviation of the compound uncertainty estimate.

Second, the uncertainty estimate was calibrated to the unit "% of *total yield*", not to the unit "yield change due to climate change". But the considerations above lead to an assumption for the effects of adaptation as a proportion of "*yield change due to climate change*". How does this difference affect the simplified model for the uncertainty analysis? The uncertainty about the "yield change due to climate change" is part of the overall uncertainty about the total yield. As such it can be reflected in the overall formula.

Apart from the reduction of uncertainty for adaptation the relationship between step 6 and the previous result is again reproduced by a multiplication. Step 7 once more represents a multiplicative relationship as it stands for a simple geographical extension of the results from the previous step.

2.8 Identification of correlation coefficients

If an unexpectedly low value in one of the steps increases the likelihood that a value of a later step is either high or low, this can be reproduced in the simulation via the introduction of correlation coefficients. It is examined whether such correlations are likely between any of the eight steps:

There is no apparent reason to incorporate a correlation coefficient between steps 1 and 2. Steps 3 and 4 are geographical extensions of the previous results and as such don't need a correlation coefficient to any of the previous PDFs. For step 5, if in the previous PDFs the simulation had chosen unusually low yields, the positive effect of fertilization would also tend to be lower, increasing uncertainty. To remain on the conservative side, it is assumed that this effect is already captured because step 5 is related to the previous steps via a multiplication. No correlation coefficient is introduced.

For step 6, the fact that adaptation generally reduces yield losses and therefore uncertainty for negative results is included in the simulation structure. But it is conceivable that the magnitude of the stochastic climate change impacts from previous steps influences the adaptive capacity in the agricultural sector. An indicator that this may be so is the scientific evidence from the IPCC Fourth Assessment Report (Easterling et al. 2007: 295ff). There, it is stated that the benefits of adaptation tend to level off with increasing temperature changes while potential negative impacts increase. Similarly, the adaptive capacity may depend not only on the temperature change realised, but also on the precipitation pattern and generally the severity of yield losses through climate change. The realisable adaptive capacity of poor subsistence farming and/or herding communities is generally considered to be very low. This would suggest a positive correlation coefficient, as an unusually low yield result in steps 1 and 2 would lead to unusually low adaptation gains.

For low to moderate warming on the other hand, the IPCC Fourth Assessment Report suggests rising relative benefits of adaptation up to a point. This would recommend a negative correlation coefficient. However, pressure to cultivate marginal land or to adopt unsustainable cultivation practices as yields drop may increase land degradation and endanger biodiversity of both wild and domestic species and thus counteract the positive effect of adaptation. Furthermore, increased irrigation demand combined with decreased rainfall adds another challenge to future water and food security. (Easterling et al. 2007: 300)

Therefore, a negative correlation coefficient seems to be suitable for moderate yield changes, and a positive coefficient for further climate change induced yield changes. Here, a negative correlation coefficient of −0.5 between PDF 6 and the PDFs 1 and 2 is employed to assure conservative estimates that do not overrate uncertainty: a negative coefficient leads to lower estimates of uncertainty. −0.5 is a sufficiently strong negative correlation coefficient taking into account the range of arguments for a positive correlation coefficient.

Step 7 again is a simple geographical extension of the previous results which does not make a correlation coefficient necessary.

2.9 Studies from Darwin and Morita

As described above, Tol uses not only the three studies working with the field study results from Rosenzweig and Parry (1994), but also three other studies. There is no guarantee that the inclusion of more studies automatically improves the result and reduces uncertainty. Rescher (1998: 91) remarks on the issue:

> The average will always be closer to the actual outcome than the worst of its component individual predictions. This is pretty much all that can be said in favour of averaging unqualified and in general. It is clearly false that the average were always better than most individual predictors.

This may also be true for the average of various studies used as an input to FUND. One indication for this is the effect on uncertainty of the inclusion of one more study into FUND in addition to five studies already used earlier. Tol gives his own specifications of the standard deviations describing uncertainty. These standard deviations are based only on a statistical evaluation of the differences between model results, not on an evaluation of the models themselves. Due to the inclusion of a sixth study, the standard deviations for the optimal temperature increased from 0.57°C (Tol 2002b: table I, average among regions) to 2.82°C (Tol and Heinzow 2003: table 3). The optimal temperature was chosen for comparison here as it is given in the same unit in both of Tol's tables referred to and is therefore directly comparable, which is not the case for the impact caused by a certain level of temperature change.

But sometimes the average of many studies is closer to the truth than any one result of a random study. Nicholas Rescher explicitly mentions economic forecasts as a field where this was found to have been the case repeatedly (Rescher 1998: 92). To remain on the conservative side, the overall uncertainty of the agricultural input to FUND is assumed to have been reduced by the inclusion of more sources. This improvement, however, is reduced, whenever the different studies are not independent in their assumptions and structure. For example, all general equilibrium models make assumptions on the functioning of markets which do not perfectly reflect reality, but which are necessary in order to work with these models (Springer 2003: 530). And subsistence farmers without market access are not being regarded in any of the models. Furthermore, only a limited number of groups are active in the monetary assessment of climate change impacts, and most of them are based in Europe or North America (IEA Greenhouse Gas R&D Programme 1999: 3). These authors of the different studies work within a global scientific community and are probably being influenced by each other. They have read similar scientific publications and built their models on state-of-the-art knowledge. For example, all of the authors mentioned above focus on average warming and don't include extreme events adequately. They fall back on similar assumptions about future socio-economic scenarios. Their results can hardly be assumed to be perfectly independent.

Darwin uses the same general circulation models as Rosenzweig and Parry, and his general equilibrium model, FARM, is a slightly adapted version of GTAP, which was used by Tsigas et al. (1997), one of the studies included above. He doesn't consider CO_2-fertilization in his study. So for steps 1, 5, and 8 the inclusion of Darwin does not lead to a further reduction of uncertainty. For the steps 2–4, global assessment of yield changes, Darwin has developed an independent concept, which has however been criticised by Cline (2007: 11ff) as unsatisfactory to assess future yield changes. For example, new land is modelled to be taken under production at no opportunity cost – and the yield predictions for Alaska, which is responsible for most of the gains in the US, are not realistic according to Cline. Furthermore, Darwin assumes that rising prices will increase productivity and thus make up for part of the losses without taking into account corresponding losses in consumer surplus. Considering these imponderables, it is not certain that the inclusion of Darwin's study reduces the uncertainty of the yield estimates, but in order to remain on the conservative side, the standard deviations of the PDFs from steps two to four are reduced by 10%. Finally, steps six and seven, adaptation, are included implicitly in the Darwin estimate. His assumptions on adaptation have been criticised (Cline 2007: 13), as he basically assumes perfect adaptation at zero costs. Darwin himself states that his water supply assumptions are too optimistic, extreme events are not included and the ecosystem value of land has been ignored. Large amounts of additional land are being brought into production in his model to compensate for yield losses elsewhere, which may not be politically viable or desirable. Thus, following this criticism, the standard deviations of steps six and seven are not reduced.

The IEA GHG programme cooperated with Morita, to use the Asian Pacific Integrated Model in their full fuel cycle methodology. While it is a global model, its focus is the Asia-Pacific region. It consists of three sub-models: the emission model,

	Step	Probability distribution function
1	Precipitation forecast	SD = 3.1 % 
2	Field study	SD = 9 % 
3	Extrapolation to nation	SD = 9 % 
4	Extrapolation to globe	SD = 6.7 % 
5	CO_2-fertilization	± 9.2 % 
6	Adaptation, scope	± 5 % 
7	Adaptation, extrapolation	Width 5 % 
8	Global equilibrium model	Not included

Table 2.2: Overview of probability distribution functions in the uncertainty analysis of the agricultural sector of FUND; SD = standard deviation

the climate model and the impact model. The authors state that a major source of uncertainty are the regional climate predictions from global circulation models. They write that "in many instances the differences in projections between different models are of the same magnitude as the changes predicted." (IEA GHG 1999: 5) In the light of this information our uncertainty for step 1 above has probably been underestimated, and introducing Morita's results can't improve this part of the calculation. Still, as the Asian Pacific Integrated Model has a different geographical focus than the other studies, an overall uncertainty reduction of 20% for the combination of steps 1 to 8 is assumed due to the consideration of Morita's results in the calculations.

The core model formula is:

$$\left(100\% \cdot PDF_1 \cdot PDF_2 \cdot PDF_3 \cdot PDF_4 \cdot PDF_5 \cdot \left(PDF_{adaptation} + \left(1 - PDF_{adaptation}\right) \cdot 100\%\right)\right) \cdot PDF_6 \cdot PDF_7 \cdot 0.8 \tag{2.5}$$

Where PDF_i is the probability distribution function of step i, and $\text{PDF}_{adaptation}$ is the probability distribution function of how much damages can be avoided through adaptation measured in % of total yield, not in % of yield change. Table 2.2 gives an overview of the respective probability distribution functions.

The probability distribution functions for steps one to five are linked via multiplication. Then uncertainty is reduced to account for the effect of adaptation as described above. In the formula above, the part "$\cdot\left(\text{PDF}_{adaptation} + (1 - \text{PDF}_{adaptation}) \cdot 100\%\right)$" describes this reduction of uncertainty. The probability distribution functions for steps six and seven are again linked to the previous calculations via multiplication and the overall result is multiplied by 0.8 to account for the inclusion of the study by Morita. Furthermore correlation coefficients of −0.5 between the PDFs one and six as well as between PDFs two and six are introduced into the Monte Carlo analysis.

2.10 Tol's climate change yield estimate as an alternative calculation basis

In the calculations above, 100% of gross agricultural product (GAP) after climate change have been used as the metric for PDFs 1–7. Alternatively, it would have been possible to calibrate the PDFs to 100% of GAP before climate change and then use Tol's estimate of yields with climate change as the calculation basis. For example for South and South East Asia he estimated a yield reduction of 0.86%. This would translate in using 99.14% as the input into the uncertainty model.[3] Actually, the knowledge about the correct PDFs for each of the eight steps is so imprecise that for such a small difference better PDFs could hardly be developed for this version than those given above. Using 99.14% as an input, there is a very slight difference in the final result: the final standard deviations differ by 0.1%. This is negligible compared to the general uncertainty of the results here. Tol's yield change estimates are smaller for all other regions.

2.11 Results

The combined standard deviation of steps one to seven before adapting for the inclusion of the study by Morita is 5.9% of the global yield with climate change. The results of the first five simulations with 10000 runs each were 5.929%, 5.952%, 5.899%, 5.923%, and 5.928%. The result is stable from one simulation to the next and

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[3] This requires minor changes to the model, but does not affect the principle.

Monte Carlo analysis can be identified as a reliable method for these calculations. The standard deviation for the uncertainty including the study by Morita, is 4.7% of GAP.

It might be argued that the uncertainty for the 2.5°C warming has been overestimated due to the fact that some of the agricultural studies Tol has used assume stronger warming for a CO_2-doubling. The three global circulation models most frequently employed predict average global warming of 4°C, 4.2°C and 5.2°C. So the numbers Tol uses for a 2.5°C warming have partially been deduced from figures for a stronger warming. And forecasts for higher temperature changes may be fraught with a higher level of uncertainty. Morita however works with temperature increases of 1.6°C and 2.1°C (IEA Greenhouse Gas R&D Programme 1999: 9). On average, the six studies underlying FUND assumed a 3.7°C warming for CO_2-doubling in the atmosphere, which is still higher than the benchmark warming of 2.5°C.

However, this line of arguing can only apply to the uncertainty contribution of step 1. This is based upon the difference between results implied by different global circulation models, which assume a higher temperature change than 2.5°C for CO_2-doubling in the atmosphere. But as explained above, the uncertainty of how much warming is implied by a CO_2 doubling in the atmosphere was not included in the calculation of the probability distribution function of step 1, and therefore the corresponding uncertainty has certainly not been overestimated. Precipitation forecasts are not necessarily less uncertain for 2.5°C warming, as precipitation intensity and amount are expected to fluctuate over the decades in many regions as warming continues (Rosenzweig and Hillel 2005a: 250). Still, most scientists would probably agree that precipitation changes are easier to predict for 2.5°C warming than 5°C or 10°C warming. It is in accordance with the logic of forecast that the difficulty of precipitation change predictions increases with temperature change: a world that differs more from the one we live in and know is more difficult to describe than a world relatively similar to today's world. This is true even though precipitation changes for a 2.5°C warming are already very difficult to predict – and even though the precipitation amount in parts of the world may be more similar to today's precipitation amount for a 4°C warming than for a 2.5°C warming. That the actual precipitation pattern would be similar to today does not make the prediction easy – for it is not known where and for which warming the amount resembles today's precipitation. The difficulty to predict precipitation patterns and intensity does not concern this comparison between 2.5°C warming and stronger warming, as these changes were not regarded in the crop growth model.

Still, to be safely on the conservative side, the calculations were repeated with a standard deviation of 0 for the probability distribution of step 1. There was no discernable reduction in the overall standard deviation of steps 1–7. The average of 5 Monte Carlo simulations with 10000 runs each was 5.926 in the original uncertainty model and 5.963 in the test version with no uncertainty for the precipitation prediction. So uncertainty was even slightly, but not significantly increased. This may be due to the fact that there is a correlation coefficient in the uncertainty model between step one and step six. The result is thus also a strong indication, that the correlation coefficient between step 1 and step 6 was chosen sufficiently negative to assure a conservative calculation. And the comparison shows, that the final uncertainty result is definitely not an overestimate due to the input for step 1. Furthermore, a number of reasons was given above, that the uncertainty estimate of step 1 is probably rather a strong underestimate of uncertainty, not an overestimate.

Steps 2, 3, 4, 5 and 7 measure errors that are independent of the temperature change: The error of the yield model for any given temperature was determined under current conditions (step 2), equally the errors of extrapolating results to a larger geographical scope (steps 3, 4, and 7) and effects of CO_2-fertilization (step 5). The standard deviations of steps 2 to 5 and 7 are derived independently of the results from the different global circulation models. It is reasonable to assume that yield changes for a small temperature change are easier to predict than yield changes for substantial global warming. Therefore, the uncertainty estimates are an underestimate of true uncertainty. Taking into account all the imponderables of severe warming would further enhance the uncertainty estimate.

The calculation for the standard deviation of step 6 partially relies on the compound standard deviation of steps 1 through 5, so an overestimate of uncertainty in the previous steps could affect the correctness of the probability distribution function for step 6. But as was shown above, the compound uncertainty estimate of steps 1 through 5 is very likely not fundamentally affected by the differences in warming predictions for CO_2-doubling in the atmosphere. Step 8 does not contribute the compound uncertainty estimate and can therefore not be affected either by the differences in warming predictions.

In figure 2.8, standard deviations for regional uncertainty are compared to the absolute welfare changes Tol assumes for a 2.5°C warming for selected regions. He reports gains and losses for different regions between 0.17% and 0.86% of GAP (Tol and Heinzow 2003, Table 3). So the standard deviation of 4.7% calculated here is at least 5 times the welfare change, or 27 times bigger than in the region with the smallest welfare change. The 95%-confidence interval would encompass a range 20 to 108 times as big as the absolute welfare changes assumed for a 2.5°C warming in FUND (10 to 54 times the assumed welfare change in both directions).

Tol himself indicates standard deviations for his 2.5°C results (Tol and Heinzow 2003, Table 3). Depending on the region they vary between 0.21% of GAP and 1.51% of GAP. These standard deviations reflect the variation between the studies and the scenarios. It goes without saying that the results from this thesis are larger as it was intended to measure a wider range of uncertainty types. Tol himself writes about his uncertainty assessment that “models, methods and scenarios are assumed to be free of error and uncertainty, so the estimated uncertainties are lower bounds of the ‘true’ uncertainty.” (Tol 2002a: 48) Tol et al. (2003: 18) also state that the uncertainties reported for FUND are probably too low. In the uncertainty calculation above, uncertainties of the underlying steps in the agricultural studies were included. This naturally leads to higher standard deviations than the comparison of study results, where all authors worked with mean values, which will often be similar from one study to the next although the range of possible values is much wider. Furthermore, three of the six studies Tol uses are based on the same calculations except for the final equilibrium model, which must reduce his estimate of the standard deviation. The other three studies also coincide with the first three in some of the underlying data. Therefore a standard deviation 3–4 times as big as Tol’s earlier results for the standard deviation in one region seems plausible as a lower bound of the true value and further supports the conservative character of the calculations in this thesis.

Tol’s less inclusive estimates of the standard deviation are also given in figure 2.8, where three regions representing the range of results have been chosen. Both the regions for which Tol calculated the biggest standard deviation compared to the yield change (OECD-Pacific) as well as the smallest standard deviation compared to the yield change (South and South East Asia) are given, equally the regions with the biggest relative gain (OECD-America) and the biggest relative loss (South and South East Asia) according to Tol and the regions with the highest (South and South East Asia) and lowest (OECD-Pacific) relative yield changes (irrespective of the sign of the change) compared to a scenario without climate change.

Tol and Heinzow (2003: table 3) also indicate standard deviations for their estimates of the optimal temperature in each of the world regions, that is the temperature level at which they consider regional yields to be highest. They have estimated the optimal temperature levels via a regression analysis (Tol 2002b: 138). These standard deviations vary between 2°C and 4.1°C. Considering that the esti-

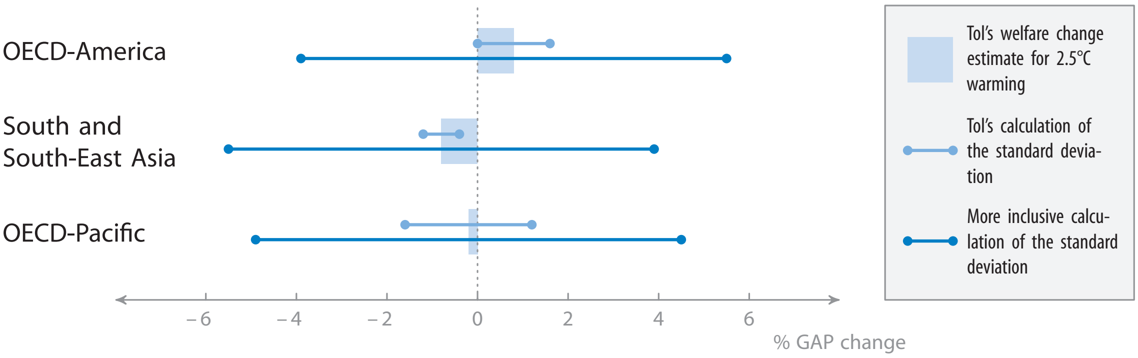

Figure 2.8: The standard deviation compared to the absolute welfare change for 2.5°C warming in FUND

mates for the optimal temperatures vary between 0.5°C and 1.7°C warming, and that a more complete uncertainty calculation would lead to higher results as was shown above, it can be said that this input to the FUND model is indeed highly uncertain.

Finally, as mentioned above, it should be kept in mind that in this thesis not the whole range of uncertainty types was included. Furthermore Tol has not included the welfare loss due to people at risk of hunger, but assumes that everybody will buy their food, in the case of negative impacts just at a higher price. This is not realistic, as a significant number of people do not have enough money to buy imported food in case of a local supply problem, and some people even lack market access. The problem is aggravated by the distribution of yield losses: developing countries are expected to be hit a lot harder by yield losses than industrialised countries (Easterling et al. 2007: 297; Tubiello and Fischer 2007: 1042; Rosenzweig and Hillel 2005b: 194ff). The welfare loss due to additional millions at risk of hunger could be higher than the welfare loss due to average yield reductions (Warren et al. 2006b: 5f).

2.12 Extension of the results to higher temperatures

To reproduce the relationship between climate change damages in the agricultural sector and different temperature levels, Tol uses a quadratic function which is defined by three points: no temperature change leads to no climate impact; a value for the optimal temperature level in various world regions is derived via a regression based on the studies by Darwin et al., Reilly et al. and Rosenzweig and Parry (Tol 2002b: 138), so this temperature defines where the first derivation of his quadratic function is 0; and finally, as described above, Tol retrieves impact values

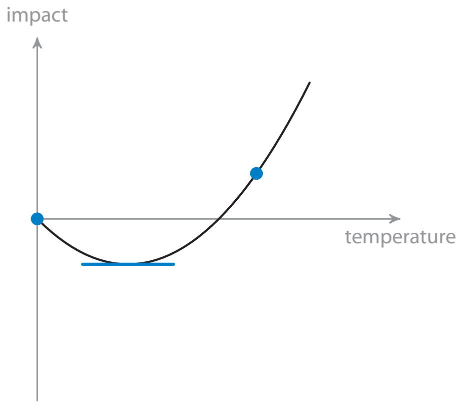

Figure 2.9: Agricultural impact calibration in FUND

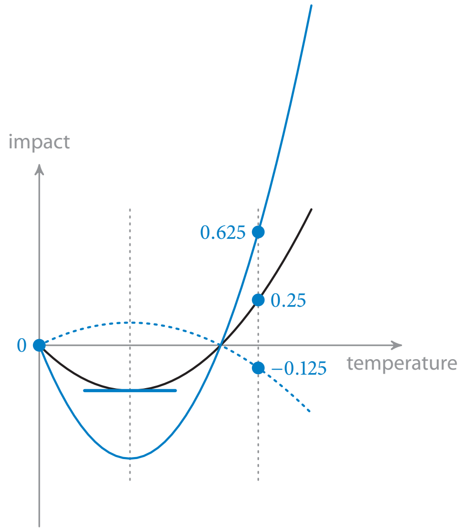

Figure 2.10: Example for the influence of a 0.375% error in the impact estimate for 2.5°C warming in FUND (numbers in % of GAP)

for a 2.5°C warming. These three conditions are sufficient to define a quadratic function. Figure 2.9 illustrates the calibration points for agricultural impacts in FUND.

In reality, the functional form is unknown. Extrapolation to higher temperatures is highly uncertain. Stern (2007: 67) actually explained that a quadratic functional form is unlikely to correctly represent real world conditions. Furthermore, it was shown above that the calibration points other than zero yield change for zero temperature change are associated with a considerable degree of uncertainty. And as these three calibration points are relatively close to each other, a small error in one of them can lead to a substantial error for scenarios with strong warming. An example can illustrate this. The optimal temperature in FUND is, according to region, between 0.51°C and 1.73°C above today's temperature. The third calibration point indicated in Tol and Heinzow (2003: 6) is the impact for 2.5°C, and the yield change for this point is consequently close to zero. Effectively, the welfare changes in the agricultural sector of FUND for a 2.5°C warming are negative in five regions and positive in four regions. All impacts are less than 1% of gross agricultural product. Now if for example an error of only 0.375% of GAP should have occurred in the development of the impact figure for a 2.5°C rise, and if the best guess value were 0.25% of GAP (a medium value in FUND), the real point would be below the x-axis or more than twice as high – and the effect on the curve at higher temperatures would be dramatic, even if the assumption of a quadratic functional form had been correct in the first place (cf. figure 2.10). In the example shown in the graph, the value below zero even leads to a shift from a minimum to a maximum – an unrealistic outcome. However, as was demonstrated above, uncertainties are much larger than 0.375% of gross agricultural product. Similarly a small shift of the optimal temperature to the left or to the right could influence impact assumptions for higher temperatures drastically. As was shown above, the value for the optimal temperature is extremely uncertain.

Above it was explained that the fact that most of the studies underlying the agricultural sector in FUND assume a higher warming than 2.5°C for a CO_2 doubling does not lead to a distortion of the uncertainty estimate. Even if this were not true, the general conclusion would still be correct. On average the six studies underlying FUND assumed a 3.7°C warming for CO_2-doubling in the atmosphere. Higher values than that may be reached within this century and considerably higher temperatures in the next century. The IPCC states that values for climate sensitivity considerably higher than 4.5°C cannot be excluded (IPCC 2007b: 12), and we might reach doubling of greenhouse gases well before the end of this century (Watson et al. 2001: question 6). But in analogy to the example above, a small error in the estimate for 3.7° warming can lead to huge errors for a warming of 6°C or more. This is all the more true as the considerable uncertainty attached to the optimal temperature leads to very high uncertainty also for temperatures only moderately higher than 2.5°C, even more so for higher temperatures.

In the following, it is shown what happens if these rules are applied although they are not reliable. The uncertainty attached to the impacts at a higher temperature of $t = 5$°C is tentatively quantified using Tol's formula for higher temperature impacts (e.g. Tol 2002b: 138):

$$f(t) = \frac{-2 \cdot A \cdot T_{opt}}{1 - 2T_{opt}} \cdot t + \frac{A}{1 - 2T_{opt}} \cdot t^2 \tag{2.6}$$

Where T_{opt} is the optimal temperature and A is the impact for 1°C warming as given in Tol and Heinzow (2003: table 3). Both values vary according to the region.

In a first step, Tol's values for standard deviations are used for the impact of a 2.5°C warming and for the optimal temperature. The impact numbers are first converted to values for a 1°C warming. Whenever T_{opt} is stochastic, stochastic T_{opt} are used for this conversion as well, as this leads to considerably smoother results across regions. Picking just one T_{opt} leads to extremely high values for Pacific OECD and extremely low values for Africa, which are caused mainly by

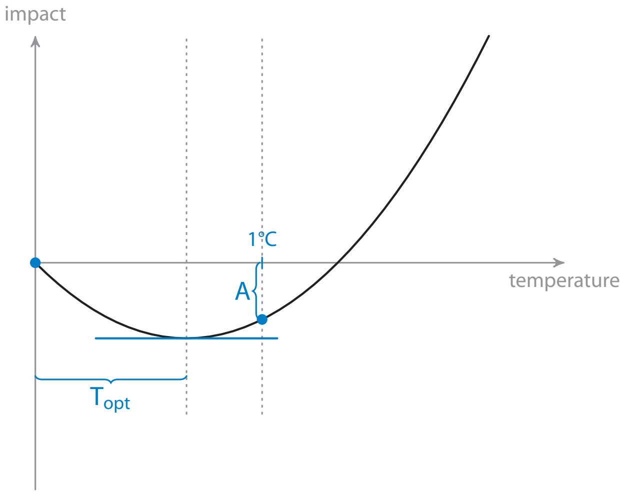

Figure 2.11: Illustration of parameters A and T_{opt} in formula 2.6 and 2.7 and table 2.3

a mathematical coincidence and do not picture the general characteristics of the assumptions.

For three of the nine regions, the formula leads to unlikely results for the values Tol indicates, as the second derivative

$$f''(t) = \frac{2A}{1 - 2T_{opt}} \tag{2.7}$$

is positive, which indicates a minimum instead of a maximum at T_{opt} where the first derivation is zero. Contrary to present scientific knowledge e.g. from Easterling et al. (2007: 286), this leads to quickly rising benefits of climate change for higher temperatures. Differing from the numbers in the tables which are compared to 1990 temperatures, the FUND model calculates with temperature changes compared to preindustrial temperatures (Tol 2002b: footnote 1). But at least for the region Middle East this cannot prevent the counterintuitive behaviour of the curve (based on data from Tol and Heinzow 2003: table 3). And when consistently applying the different base temperature, the counterintuitive behaviour remains for all three regions in question. In the following, results for the other regions are given. It must be noted, however, that for some combinations of T_{opt} and A the switch from a maximum to a minimum still occurs.

In Table 2.3 (p. 71), the 90% confidence interval is given for both a 2.5° warming and a 5°C warming. The first column shows the results when both A and T_{opt} are stochastic inputs, and the second column when only A is stochastic. For a graphical explanation of the two parameters A and T_{opt} see figure 2.11. In line with theory, the width of the 90% confidence interval for a 2.5°C warming (only A stochastic)

Region	Standard deviation from Tol		Standard deviation 3.5		Standard deviation 5.6	
	T_{opt} stochastic	T_{opt} not stochastic	T_{opt} stochastic	T_{opt} not stochastic	T_{opt} stochastic	T_{opt} not stochastic
2.5 °C Warming						
OECD-A	8.5	2.8	27.0	11.5	43.4	18.4
OECD-E	6.6	2.0	26.7	11.5	43.0	18.4
OECD-P	9.0	5.0	20.3	11.5	32.0	18.4
CEE&FSU	8.3	3.0	28.4	11.5	44.1	18.4
CPA	10.7	3.6	31.4	11.5	50.5	18.4
AFR	3.3	0.7	31.5	11.5	49.7	18.4
5 °C Warming						
OECD-A	31.9	8.9	99.2	36.9	161.4	59.1
OECD-E	26.0	7.0	100.0	40.9	163.3	65.5
OECD-P	29.3	631.3	64.0	1462.4	103.0	2339.2
CEE&FSU	31.9	10.9	105.8	42.4	169.9	67.8
CPA	41.4	13.9	120.5	43.9	203.9	70.3
AFR	13.7	3.7	126.2	61.9	196.2	99.1

Abbreviations: **OECD-A:** OECD America, **OECD-E:** OECD Europe, **OECD-P:** OECD Pacific, **CEE&FSU:** Central and Eastern Europe and the former Soviet Union, **CPA:** Centrally Planned Asia, **AFR:** Africa

Table 2.3: Width of the 90% confidence interval for 2.5° and 5°C warming given as % of regional GAP for climate change impacts in the agricultural sector as calculated in the FUND model; for a graphical clarification of the parameters A and T_{opt} see figure 2.11; own calculations based on Tol (2002 a,b) and Tol and Heinzow (2003)

is between 3 and 4 times bigger than the standard deviation. Introducing the uncertainty of T_{opt} increases the 90% confidence interval 2–4 fold. The results for the 5°C warming are again about four times bigger, a lot more than that in the case of OECD-Pacific. The result of damages more than 600% of the regional agricultural product must indeed be seen as a malfunction of the formula. It has nothing to do with reality, especially as only market impacts are included. This statement is valid even if the quadratic functional form is assumed to be correct, which is not known.

In the third and fourth column of Table 2.3, extrapolations to a 5°C warming are presented for input values closer to the uncertainty estimate derived above for the 2.5°C warming, both with and without additionally making T_{opt} a stochastic input using Tol's numbers for the standard deviation of T_{opt}. It is shown that even with a standard deviation of just 3.5% of gross agricultural product, the 90%-confidence interval for a 5°C warming exceeds 30% of the agricultural product for all regions, the uncertainty being considerably higher for some of the regions. These results are more pronounced for the calculations with stochastic T_{opt} and for a standard deviation of 5.6% of global agricultural product.

It is important to keep in mind what effect this uncertainty about higher temperature has on mitigation recommendations. As an example the following comparison is used: a policy framework that stabilizes climate change at 2°C above pre-industrial temperatures compared to a different policy set that leads to stabilization at 5°C. Low climate impacts at 2°C would actually lead to a stronger case for moving to the 2°C-path, as marginal impacts between 2°C and 5°C are higher for any given impact level at 5°C if the 2°C warming was actually beneficial or only slightly negative, compared to a world in which most of the damages accrue during the first 2 degrees of warming. For the model's impact estimate at 5°C of course the opposite is true: a high result leads to stronger support for an ambitious mitigation strategy than low impact estimates. Thus comparably certain findings about low impacts at 2°C warming combined with very uncertain estimates for 5°C would support strong mitigation: what would be known about 2°C would indicate that the world at this temperature level was a very nice place to live in, and what would be known about 5°C would be very little, mostly that the risk for high impacts existed. But usually the opposite conclusion is being drawn: where models find comparably low impacts for 2 or 2.5°C warming, they recommend weak mitigation, assuming that the same low impacts will occur at higher temperatures, even if the model results are highly uncertain for those temperature ranges.

Table 2.4 summarizes current qualitative scientific knowledge about the effect of higher temperatures on the steps 1–8 identified above.

Finally, the changing future world almost certainly will have an effect on climate change impacts in the agricultural sector. For example, the growing population will increase the pressure on world agriculture to produce more food and fibre for everybody. Parry et al. (2004: 64) assume that by the 2080s food production in the scenario without climate change grows from 1800 million t/y today to about 4000 million t/y. This implies an intensive agriculture, which might make it more difficult than in today's system to offset climate change impacts by yield-increasing measures. The danger of erosion and the demand on water resources is likely to increase even without considering climate change.

2.13 DICE

DICE used to be based on just one agricultural study by Darwin (Nordhaus and Boyer 2000: 74), which is one of the six studies Tol uses. Furthermore, the study by

Step of calculation	Effect of higher temperatures
Precipitation	Relationship possibly highly non-linear, 1st derivation of local precipitation = f(temperature) is unknown; uncertainty increases in the beginning, might be stable later as switching precipitation regimes are hard to predict from the beginning
Field study	1st derivation of yield change impacts = f(temperature) is positive for warming above 2.5°C, the functional form unknown; uncertainty increases as the world changes more and more away from known conditions
Field study to national results	Similar uncertainty for higher temperatures assumed
National results to global results	Similar uncertainty for higher temperatures assumed
CO_2-fertilization	The world changes away from known conditions similar to those in laboratory and field studies today, which increases uncertainty; fertilization effect increases less than linearly with the concentration (Cline 2007), which reduces uncertainty.
Adaptation at the field-level	AR4 predicts that a smaller percentage of higher losses will be avoidable through adaptation; uncertainty increases
Adaptation results to global level	Similar uncertainty for higher temperatures
Global equilibrium model	Once yield losses occur in most world regions, the potential of international trade to prevent steep price increases diminishes. The effect of highly inelastic demand leading to welfare losses higher than yield losses will be even more pronounced.

Table 2.4: The effect of higher temperatures than 2.5°C on uncertainty

Darwin has been criticised to be unrealistic in some key points (Cline 2007: 11ff). Therefore the representation of agriculture in DICE could be assumed to convey more uncertainty than in FUND. The newest version, however, DICE 2007 (Nordhaus 2007a: 23), draws on one additional source of information, the calculations from Cline (2007). It is now not easy without a detailed analysis to say whether DICE or FUND reaches a higher level of certainty. The study by Cline is half based on a Ricardian analysis of empirical findings on agriculture and half on similar data as the studies underlying FUND. He meets similar difficulties as his colleagues whose studies were analysed above. It is unlikely that uncertainty in the agricultural sector of DICE is substantially lower than in FUND. Nordhaus himself worked on an uncertainty estimate of DICE (Nordhaus 2007b: chapter VII). However, he did not venture to calculate the uncertainty of parameters like agricultural impacts, but rather checked the effect of different assumptions for eight parameter on the final modelling result. He found that the impact coefficient has a strong influence on the cost of carbon, but a small influence on the emissions in 2100.

2.14 Conclusions with respect to hypothesis 1

The uncertainties underlying the agricultural impact function in FUND were assessed in detail. Although not all uncertainty types could be quantified, the standard deviation of welfare changes in the sector triggered by a 2.5° warming was between 5 and 27 times the welfare change itself, depending on the region. A conservative estimate of the 95%-confidence interval encompasses a range 20 to 108 times as big as the absolute welfare changes assumed for a 2.5°C warming in FUND. Uncertainty increases further for results at higher temperatures and other models can't be expected to perform better. Hypothesis 1 can therefore be accepted.

The calculations in this thesis are based on the best available estimates, whose reliability is not always satisfactory. But so are the calculations underlying FUND. If anybody should doubt the value of the numerical results due to uncertainties in the calculations above, the point remains essentially the same: the agricultural impact functions in FUND and DICE still involve a very high level of uncertainty.

Quite often at the beginning of IAM studies, authors stress the considerable uncertainty inherent in their models (e.g. Tol 2002b: 136; Nordhaus 2007b: 44), but this consciousness seems to fade in the course of the papers: at the end very clear conclusions are drawn from the model results as to marginal damage costs, the economic efficiency of the Kyoto Protocol or a certain optimal emission abatement level. The results of this thesis can be interpreted as a call to keep the uncertainties involved in mind at all stages of IAM-work, and to use adequate techniques to deal with them. Doubts can be cast on whether very detailed models are really able to significantly reduce uncertainty compared to more general approaches based on expert judgement and allowing for uncertainty to be treated explicitly.

Part II

Accommodating subjectivity – a different approach to cost-benefit analysis

In this part, the critique of the objectivity claim from the preceding part is taken up and decision analysis is assessed and scrutinized as a possible alternative. The following assessment of the applicability of decision analysis to cost-benefit analysis consists of four parts:

1. A critique of the objectivity claim in cost-benefit analysis of climate change.
2. A description of the theory of decision analysis; herein special emphasis is put on those texts that were named to be the theoretical background of the model PAGE2002.
3. Assessment of the applicability of the theory to cost-benefit analysis of climate change; as the theoretical foundations discussed in this chapter were not originally intended for cost-benefit analysis of climate change, it is assessed in how far they can be applied to a model comparing costs and benefits of climate change mitigation and adaptation. Alternatives to cost-benefit analysis like for example the tolerable window approach (Graßl et al. 2003: 8, 22) and multi-attribute approaches (Faucheux and Noel 2001: 353ff) can be valuable concepts for the process of decision making, but they are not in the focus here.
4. The implementation of the theory of decision analysis in the model PAGE2002; in view of the results from bullet point number two and possible adaptations that need to be made to the theory of decision analysis in this special context, the implementation in the model PAGE2002 is assessed.

3

Critique of claiming objectivity in the cost-benefit analysis of climate change

In the foreword to the book by Watson and Buede (1987), Baruch Fischhoff describes decision analysis as a method to improve decision-making with a sensitivity for individuals and single decision-problems. The book challenges the assumption, that people have articulate values and beliefs. Therefore, according to this theory, tools to aid decision making can not be simple procedures that automatically derive the right course of action from the pre-existent perceptions of individuals. Rather, "decision makers are seen as synthesizing those perceptions from pieces of experience. In this conception, the aide may prompt them regarding where to look, suggest alternative perspectives, …" (p.xvi). But the aide (e.g. the model) could not relieve a person from ultimately making the decision him- or herself. This does not imply, that all models should be constructed by problem owners or decision makers. It can't be the job of politicians to produce scientific prognoses and scenarios, say on the likelihood of global warming linked to a certain concentration of greenhouse gases in the atmosphere. But it is explicitly intended in the description by Fischhoff that the advice of a decision tool may be disregarded, for example when its complexities lead to the loss of cognitive control of the problem. And it is pointed out that the choice of normative settings should be entirely in the realm of the decision makers, even if scientific models often make assumptions on these ethical and normative settings.

Hope and Owen (1986) apply the criticism of exaggerated faith in decision tools to the discussion of cost benefit analysis of energy and environmental problems. They claim that these cost benefit analyses are not objective, although they are often presented as value-free and neutral inputs to the policy process (Hope and Owen 1986: 862). According to them, the subjective valuation of the analyst enters the calculations in numerous ways. They do not contend the desirability of a tool that could give objective answers to the questions how to deal with energy and environmental issues. Rather they contend the possibility of such a procedure and develop their recommendations for decision making from this claim of impossibility. It is therefore necessary to return the attention to the traditional cost benefit analysis and check to what extent the claim from Hope and Owen is correct.

Indeed, for the cost benefit analysis of climate change the pervasive influence of ethics and uncertainty is entirely plausible. Hohmeyer (1995: 73–78) describes clearly the overwhelming influence of ethical parameters like the valuation of human lives and the discount factor on the final results. These numbers can not be objectively derived by observing the real world, but they are a necessary input to a complete cost benefit analysis. The state of the art cost-benefit analyses that are characterised by the search for utmost objectivity like FUND and DICE do not clarify the effect of these ethical assumptions on the results. For example, neither of the two models includes estimates of people dying of hunger, thus implicitly setting the value of a human life lost due to hunger to zero.

It is not easy to make sensitivity analyses for all subjective parameters, as different ethical choices simultaneously influence the result. A rather complex table is necessary to produce an overview of different combinations of the discount factor, the value of human life, the aversion to risk and the aversion to inequality, to name only a few. The task becomes even less tangible, when all the different uncertainties are considered.

A defender of the objectivity claim of cost benefit analysis may state, that the valuation of the risk to lose a human life is ultimately observable in real life, just as risk and inequality aversion. However, these observable values are very divergent in different situations, and ultimately the analyst decides which value to use. The decision is further complicated, when the people who cause change are not those who suffer or gain from the consequences – and when the monetary valuations of the first substantially differ from the valuations of the latter. This is for example the case with climate change, where people in industrialised countries emit substantially more greenhouse gases per capita and people in developing countries are more severely threatened by yield losses due to climate change.

And even if the results of a cost benefit analysis were displayed in a way such as to clarify the influence of ethical choices, a range of subjective decisions of the analyst would still enter the calculations. For example the analyst needs to decide how many contingent damages to take into account and where to make a cut and define the borders of the analysis input. For example the yield losses due to climate change could simply be valued at current or future market prices; or the analysis could be more complete and include the suffering due to additional hunger in some countries; even more complete but also more difficult to value would be the effects of conflict caused by food and water scarcity in those countries. This chain of consequences could be continued for a long time. But no cost benefit analysis can include all contingent effects. So a cut has to be made somewhere to define how much to include, and this definition of the horizon is necessarily a subjective one made by the analyst. And even within this defined scope of the analysis, subjective decisions are hard to avoid: the case of climate change is an example where the speed and severity of the consequences of rising greenhouse gas concentrations are uncertain as was demonstrated in Part 1. Often different sources give distinctly different numbers as to the scope of the effects of a certain amount of emissions. The analyst can try to define criteria so as to objectively choose which of the numbers to use – but ultimately the definition of the criteria will have a subjective dimension, and the choice of input numbers to the cost benefit analysis retains an important influence on the final result.

It has been claimed before that there is too much uncertainty attached to monetary valuations of climate change to use the concept at all (European Commission 1999: chapter 2.6). But the claim brought forward by Hope and Owen is not quite so strong – or more ambitious in a different way. Hope and Owen state that a different treatment of uncertainty is possible so that the monetary valuation of climate change impacts does deliver interesting information, if no exact results.

The differing positions on dealing with uncertainty go back to an old controversy about measuring probabilities. The relative frequency theories hold that the probability of an event is the long-run frequency with which it occurs in an infinite repetition of an experiment. Probability is seen as an objective characteristic of the external world or it is claimed that a probability statement describes the objective tendency of a system to produce certain results. Subjective theories, on the other hand, state that probability is a property of the individual's subjective perception or state of knowledge. As such they describe degrees of belief. Despite the rejection of the notion of objective probabilities, subjective theories equally rely on a set of axioms and on principles of consistency. This assures that the subjective degrees of belief are still rational. The rules of probability calculus can thus be used if the individual wishes to express his or her judgement in such a coherent way. Decision analysis adopts this subjective approach to describing the measurement of probability. (Watson and Buede 1987: 30)

Whether probabilities theoretically exist as an objective measure of the external world or not, in Part 1 of this thesis it was demonstrated that an objective representation of reality in cost benefit analysis of climate change has indeed not yet been accomplished. No model is clearly confirmed in all sub-models and without any arbitrary assumptions. However, the authors of traditional cost benefit analysis of climate change are aware of this fact (for example Nordhaus 2007b: 74; Tol 2002b: 137). So the dispute is not so much about the impossibility of complete objectivity in these models, but rather how to deal with the aspect. Here two different types of models have been developed in the past. The difference between these two approaches is less pronounced for the question of how to deal with normative assumptions. The only possibility to do this is a clear indication of the normative assumptions employed in the models combined with an adequate sensitivity analysis. But the way of dealing with uncertainty is different for the two approaches:

There are those applying the traditional approach connected to rational choice theory, like FUND (Tol 2002a,b) and DICE (Nordhaus and Boyer 2000). Their way to deal with the problem is a strong effort to reach as much objectivity as possible. Hope and Owen in their critique of the traditional approach, on the other hand, claim that a model should rather openly admit to the unavoidable subjectivity and be careful not to create a wrong impression of objectivity. This way a tool can be developed that helps the decision makers to clearly and consistently look at their own values and beliefs. So the claim of decision analysis is not only that objectivity is impossible to achieve. The claim includes that it is impossible to get meaningfully close to objectivity in cost benefit analysis of climate change – and that a fundamentally different way needs to be found how to deal with this fact. Modellers from the school of traditional cost benefit analysis deduce concrete recommendations for action from their models. Consistent application of decision analysis would supply a tool which the decision maker can use to arrive at his or her own conclusion. Or, as Hope and Owen write: “Using Paretian cost benefit analysis as a primary input in environmental decision-making would mean handing over an enormous amount of power to the analyst, who is unelected and unaccountable. […] It is unlikely that society would wish to do this.” (Hope and Owen 1986: 855)

Overview of axioms underlying the two theoretical approaches to deal with uncertainty as elaborated above:

Traditional cost benefit analysis based on rational choice theory:

- objectivity as a necessary characteristic of science
- desire to strive for as much objectivity as possible during the construction of the model in order to maintain the claim that the model is sufficiently

objective for the task at hand and does not reflect the opinion of the modeller to a degree that contradicts the objectivity claim
- deduction of concrete recommendations for action from the model

Tool developed along the lines of decision analysis:

- objectivity is impossible to reach in many cases
- necessity to openly admit the lack of objectivity; it is argued that the clear indication of subjective model inputs is the best way to increase the objectivity of the model
- help the decision maker to arrive at own conclusions

4

Decision analysis as a an alternative theoretical foundation for cost-benefit analysis of climate change

Above, the rationale for abandoning traditional, seemingly objective cost benefit analysis for certain problems was explained. Below, the possible alternative outlined by Hope and Owen is analysed. They suggest, among other tools, a form of cost-benefit analysis based on decision analysis.

The model PAGE is an attempt to realize this alternative approach. It is a cost-benefit model of climate change, but contrary to FUND and DICE it is built upon the theory of decision analysis as described in Watson and Buede (1987) and its application to modelling as given in Phillips (1984: 35–46). (Hope 2008b)

In this chapter, the possibilities of applying this theory to a cost-benefit model of climate change are assessed. First, the theoretical foundations as given in Watson and Buede (1987) and Phillips (1984: 35-46) are described. Their description of decision analysis is taken as the basis of all further application of the theory in this dissertation. This is suitable, because their form of decision analysis was used as a theoretical foundation for the PAGE model (Hope 2008b). Second, the applicability of this theory to cost-benefit analysis of climate change in general is assessed.

4.1 Decision analysis – the theory

Watson and Buede (1987) have provided a useful synthesis of the principles and practice of decision analysis. Decision analysis was developed for decision making problems very different from the question of designing adequate climate policies. Therefore, an application of the theoretical concept to cost benefit models is not straightforward. The goal of decision analysis is primarily to provide a framework for individual decision makers to connect their judgements in a consistent way (p.70). According to Watson and Buede, traditional cost benefit analysis is a rather specialized tool designed specifically for the economic appraisal of social projects, which differs from approaches of decision analysis (p. 69). Other distinctions between cost-benefit analysis and the theoretical concept decision analysis identified by Watson and Buede are the lack of equity-considerations in many examples of cost-benefit analysis and the assumption of additivity of welfare components, which is indispensable for traditional cost benefit analysis (p. 70). But the main difference according to the authors is the claim of objectivity usually made by the modellers using cost-benefit analysis. Therefore, if a type of cost-benefit model were developed that drops the claim of objectivity, a certain similarity of methods can be established. This similarity is for example expressed in the fact, that both employ multi-attribute value functions to aid decision-making. Still, not all characteristics are directly applicable to cost-benefit analysis of climate change. In the following, first the general principles of decision analysis are outlined in this chapter, then the applicability to cost-benefit analysis of climate change will be treated separately.

Decision analysis was developed in response to perceived inadequacies of other methods like operational research and the crude application of rational choice paradigms to real world problems. New requirements to scientific decision aides were formulated, among which

- to involve the decision maker and/or the problem owner in the analysis; the problem owner may here be understood to be a person intimately affected by the decision, even if he or she is not necessarily entitled to make the decision – actually no single person, group, nation or any institution can decide on the global mitigation path
- to appreciate the organizational context
- to explore goals, their creation and their expression as well as the best way to achieve a given goal (Watson and Buede 1987: 15f).

To achieve these goals, an iterative and flexible way of thinking about a problem is necessary. At the same time, a scientific aide to decision making may not disappear in the cloudiness of avoiding all general statements. Mathematical algorithms that help maintaining consistency are therefore a crucial characteristic of decision analysis. (Watson and Buede 1987: 17)

The following four requirements have been claimed to apply to any approach of decision analysis (Watson and Buede 1987: chapter 3):

- a set of rules defining what it is to be rational

- the possibility for problem owners to articulate their preferences and perceptions of uncertainties in the process
- a description of rationality in the face of perceptions and uncertainty
- a calculus for steering the thinking of the decision-makers through complex problems thus safeguarding consistency.

Rationality is meant to describe coherent action according to a set of rules, which the decision maker wishes to adopt (p. 12). Value functions, subjective probabilities and risk preferences are concepts that are commonly applied in decision analysis. For a detailed description see Watson and Buede (1987: chapter 3).

Phillips (1984) suggests a type of model relying on the principles of decision analysis, which he calls requisite. These models are generated by the interaction between specialists and problem owners. The specialists are responsible for providing the form, the problem owners for the content. Both specialists and problem owners work together to encode the content in a form compatible with the model (p.35f). A requisite decision model attempts to capture the value judgements, and their relative importance, of the group designing the model. Even if no member of the group agrees with all these judgements represented in the model, a social group model evolves describing a shared view on the structure and relevant parameters of the problem. Wherever beliefs of single group members differ from those integrated into the model, alternative settings can be tried to assess the effect of changing these inputs. (Phillips 1984: 32f)

There are obvious links between the system that the model represents and the model itself. People use the reality they know as an input to the model, and the reality they shape in the future may well be influenced by the outcome of the model. The requisite decision model is a deliberately subjective representation of a part of reality. The process of developing the model as well as the model itself help decision makers to identify their beliefs and values as well as to capture and penetrate the complexity of the problem and spur creativity during the search for solutions. (Phillips 1984: 33f)

The model can be developed either in a group process, or the specialist constructing the model could build it upon a succession of discussions with various problem owners. In both cases the process is iterative and problem owners give feedback to preliminary versions of the model (Phillips 1984: 36). When no new intuitions and ideas for improvements exist in the group, the model may be called requisite and thus sufficient for its purpose: the analysis of the decision. But the model will always be a statement in the form "if the values and perceptions are

Definition	Model is requisite when its form and content are sufficient to solve the problem
Representation	Requisite model represents a shared social reality
Generation	Through iterative interaction among specialists and problem owners
Process	Uses sense of unease arising from discrepancy between holistic judgements and model results in sensitivity analyses
Criterion	Model is requisite when no new intuitions arise
Model status	Requisite model is at best conditionally prescriptive
Goal	To serve as guide to action, to help problem owners construct new reality

Table 4.1: Features of requisite decision models and the process of generating them. Source: Phillips (1984: 40)

as entered into the model, then the derived results materialize". It is not claimed, that the model correctly represents reality, but rather the perceptions of those who constructed the model. And as time passes, new knowledge evolves and conditions change, a reformulation of the model may well become necessary. Table 4.1 gives an overview of Phillips' concept of requisite models.

This model technique was not developed for the support of whole societies to decide how to deal with climate change. It is therefore not directly applicable to cost-benefit analysis of climate change. But it is based on decision analysis (Phillips 1984: 35) and at least in one crucial point it is closer to the reality of cost-benefit modelling than the concept of decision analysis described by Watson and Buede: the requisite decision models are developed in a group process for group decisions, whereas Watson and Buede describe decision analysis as a "normative theory for how an individual decision-maker might think through his or her decisions and determine sensible actions; it does not set out to do the same for groups of people, or for corporations, or for public bodies." (p.5) They put forward that organizations make decisions in a different way than individuals do, and that applying decision analysis to organizations will require careful argument (Watson and Buede 1987: 106). Yet, Watson and Buede also report that, contrary to the roots of the theory, decision analysis has in practice frequently been employed for decisions of organizations or public bodies – and that there is ample room for the improvement of decisions in organizations. The tool of requisite decision models as put forward by Phillips was called one of the most important applications for this purpose (Watson and Buede 1987: 115).

Apart from the concept of requisite models for decision analysis, a very diverse literature exists on decision making in organizations. Some key results are summarized in the following. None of these approaches was developed especially for the context of climate change. They are briefly described here, because one of the main differences between the description of decision analysis above and any approach needed to deal with the problem of climate change is the fact that the theory above was developed for individuals, not for decision making in societies. Therefore a few relevant concepts from the literature on decisions made by groups of people like for example in an organization are presented here. The description is based on Watson and Buede (1987: 102ff).

Simon (1955) brought forward a description of how people in administrations typically make group decisions. He emphasizes that the choice of strategy may not be left to the single persons working in the administration as it is crucial that they should know each others' strategies. He describes the problem of coordination as crucial to effectively steer group behavior in decision processes (p. 49ff). One possible form of organizing a formalized bureaucracy is the development of a set of rules which prescribe the action to be taken in a certain situation (p. 69).

From political science, explanations are offered how decisions are arrived at in politics. Here the confrontation of different pressure groups in the political arena is in the focus of interest. The outcome of a decision is determined not by rational decision making, but rather by the confrontation of these groups (Watson and Buede 1987: 105).

A contribution of social psychology may also be relevant for the context of this chapter: Janis (1972) identified the phenomenon of "groupthink". He describes that group decisions are often subject to certain deformations, namely an illusion that the group can not be subject to error, a common belief in the morality of the group and a tendency to put pressure on group members with a different position to conform to the group standard (p. 2ff). The danger of groupthink exists especially when a group is

- highly cohesive
- insulated from many external influences
- not systematically evaluating alternatives
- subject to a directing leader
- in a condition of high stress. (p. 197ff)

This finding may be relevant for the concept of requisite decision models outlined above. The requisite decision models rely on a group process to improve decision making, whereas Janis describes that under certain conditions groupthink can actually deteriorate the quality of decision making. An important contribution to avoiding the dangers of groupthink in the process of developing a requisite decision model is the role of the external specialists providing the form of the model (cf. Phillips 1984: 44; Janis 1972: 208). This scientific embedding of the group discussion process delivers a stimulus to evaluate alternatives and provides external input to the problem owners. Furthermore, as calculus is employed to clearly display the meaning of consistency for the problem at hand, the group has a certain safeguard against getting lost in the dynamics of the group process. Requisite decision models might be described as a tool that attempts to extract the benefits of group decision processes compared to individual decision making while trying to minimize the dangers of groupthink. Still, these dangers can not be excluded and it is valuable to keep the concept of groupthink in mind for the further evaluation of the application of decision analysis to cost-benefit analysis of climate change. The main feature of requisite decision models is the establishment of consistency in the model, not the eradication of defective consequences of group processes.

The decision making process of determining public policy is an issue that has raised considerable interest. Analyses of public policy need to be open in a democracy, which further recommends the application of decision analysis techniques. According to Watson and Buede (1987: 115), the best known technique for analyzing public policy is cost-benefit analysis. It has been outlined above that the application of the principles of decision analysis to cost-benefit analysis is not simple. But this citation from the literature shows, that cost-benefit analysis has been connected to decision analysis before PAGE, when the application of decision analysis to public policy decisions was endeavoured. However, it is clear that the traditional form does not adequately fulfil the principles of decision analysis (cf. Watson and Buede 1987: 115).

Other attempts to make multi-attribute value functions useful for the domain of public policy were for example a study of nuclear waste management in the United Kingdom (Watson 1985) and a decision process around the question whether to build a solid-waste shredding plant (Chen et al. 1979). Neither of these tried to monetarize the whole range of consequences. Rather, impacts were given in various metrics. Weights for the importance of each of these were used. In the study about nuclear waste management, the results were given for four different sets of weights that were supposed to approximately cover the different beliefs and preferences in the population. Thus the influence of the subjective value judgements and the implications of different views became clear. In the latter study, local politicians themselves were asked to provide weights for the analysis. The analysts helped each member of the council to elicit values. The result was not a fix answer what the decision ought to be, but rather a shared understanding of the problem made the final decision easier.

Howard (1975) brought forward another idea how to use the structure of decision analysis for decisions about public policy: he suggested that three independent bodies of people should be established for solving the problems of society. The first would be responsible for defining the problem and determining the possible alternative solutions. The second would describe the consequences of each of these alternatives. The third would elicit the preferences of society. The first two bodies would be technical and scientific; the third might consist of democratically elected personnel (p. 190). This split into three independent bodies contributing to decision-making could be seen as an ideal form rather than a realistic prescription for the majority of public policy issues.

Finally, it may be mentioned, that the development of cheap and powerful computers has had an influence on the possibilities to use decision analysis techniques in the public policy domain. With assistance of software, it is easy to explore the consequences of different and even complex alternatives for action, values, and beliefs. Probability distribution functions can be used just as easily as definite values where these are not known, and the meaning of consistency can be established for problems that are far too complicated to be grasped intuitively. At the same time, the use of such software can obscure rather than enlighten the situation, if the user does not sufficiently understand it.

4.2 Applying decision analysis to cost-benefit analysis of climate change

The key message from the description of decision analysis above based on Watson and Buede (1987) and Phillips (1984) is, that a model based on this theory allows the decision maker to use the model as an aide to structure ideas and thus reach a coherent decision based on his or her own values.

To assess the applicability of this approach to modelling in the context of climate change, it is necessary to differentiate between different types of models in this field. The concept above is hardly applicable to the construction of a highly complex coupled atmospheric-ocean climate model. The knowledge on the physical and chemical processes in the atmosphere and in the oceans is too specific for anybody else but an expert to endeavour the construction of a new climate model. A tool to structure a decision maker's ideas on the atmospheric processes would not lead to a valuable result. If the model approach described above is applied to the modelling of climate change, it would need to be a sufficiently simple integrated assessment model into which the results from complex specialized models are integrated as an input. The problem owner may still apply own judgement on the uncertainty of these results from other models, for example based on the range of results from different modelling approaches or from general knowledge on the difficulties of modelling.

4.2.1 Key requirements

For a decision analysis model as described above based on Watson and Buede (1987) and Phillips (1984), the following requirements can be identified:

1. provide a description of rationality, also in the face of uncertainty; for example the concepts of value functions, probabilities and risk preference are core concepts of decision analysis
2. employ calculus to check thoughts for coherence
3. reflect the values and beliefs of problem owners
4. develop the model in an iterative, interactive and consultative process between specialists and problem owners
5. use problem owner's sense of unease to improve the model
6. check goals as well as the best way to achieve a given goal.

Cost-benefit analysis of climate change deals with an issue of public policy. In this context the following two requirements are additionally identified as necessary to achieve the characteristics named above:

7. transparency of the model inputs and structure
8. open and easy access to all the details of the model

Unless they are fulfilled, the public as a key problem owner has no possibility to judge the adequacy of the model according to their beliefs or even change parameter values to reflect their own values and suppositions.

4.2.2 Particularities of cost-benefit analysis of climate change

What do all these requirements mean for cost-benefit analysis of climate change? To what extent can they be adapted to this tool for supporting a complex decision of public policy? First, the key message identified above shall be looked at in more detail. A model based on this theory shall enable the decision maker to better understand the problem and develop coherent solutions. It shall not provide a ready-made solution and it shall not deliver a false impression of objectivity. For cost-benefit analysis, this means that the recommendations from the model should be framed as statements of the type "if the assumptions and values are set as in the model, then the given result follows rationally", and not as absolute recommendations of the type "you should do the following".

In the context of climate change it is necessary to distinguish between decision makers and problem owners to judge to which extent the key message can be realized in the respective modeling. No fundamental problem was identified that would prevent the application of this key concept to cost-benefit analysis of climate change to any single decision maker with enough time on his or her hands. It can be possible to develop a cost-benefit model of climate change that reflects the values and assumptions of a given decision maker and provides a rational and coherent structure for these settings. Such a model can help the decision maker to better understand climate change and climate change mitigation and to gain more coherence in dealing with the issue. However, problem owners were defined as persons intimately affected by a decision, even if they are not necessarily entitled to make the decision. Future generations are definitely and probably severely affected by decisions made today on climate change mitigation. But it is impossible to involve these problem owners in the analysis. This is a serious limitation, which however applies to any method of decision making in the context of climate change.

Cost-benefit analysis of climate change differs from the tasks for which decision analysis was developed in several points:

1. Climate change is a problem of public policy.
2. Climate change is an international problem for which "the" decision maker does not exist.
3. Climate change impacts affect people all over the world and far into the future; this is a scope far wider than decision makers typically consider.
4. Cost-benefit analysis relies on the monetisation of all aspects of the problem, which is not the usual way for decision makers to articulate their values.
5. The combination of the complexity of climate change itself and the task of monetisation leads to a model that is necessarily too complicated for a public policy decision maker to assist during all major steps of its development

With the Intergovernmental Panel on Climate Change (IPCC) a scientific body exists, that compiles the state of the art of scientific knowledge on climate change and produces summaries, to which all governments of the world agree. The processes of scientific research on climate change and the debate about political action are to a certain extent separated by this structure. Still, the publications by the IPCC don't deliver exact predictions or numbers on all relevant points, so the decision makers can't avoid their responsibility to assess their own beliefs. For example, figures from two different sources are given on the expected number of people at risk of hunger, but the two sources give different numbers, and both give different numbers for scenarios with and without CO_2-fertilization. The IPCC does not attempt to predict the exact intensity of this fertilization effect. And from the underlying literature it becomes clear that quite a range of other factors contribute to uncertainty like pests and weeds, water logging and extreme weather events. Thus, no exact numbers can be taken from the IPCC report. Furthermore the IPCC does not make recommendations on values such as risk aversion or the value of equity.

4.2.3 Applicability of the requirements of decision analysis to cost-benefit analysis of climate change

Above, the characteristics of a model based on decision analysis were identified. Equally, the particularities of the subject at hand were listed, namely the differences between cost-benefit analysis of climate change and problems for which decision analysis was originally intended. In this subchapter, the requirements are one by one scrutinized for applicability in cost-benefit analysis of climate change:

1. Provide a description of rationality, also in the face of uncertainty; in particular the concepts of value functions, probabilities and risk preference are core concepts of decision analysis.

This concept of rationality is given by the principles of cost-benefit analysis. Rational in cost-benefit analysis is any action for which the benefits are larger than the costs, including the opportunity costs. Value functions, probabilities and risk preferences are all common features of a cost-benefit analysis. Of course, this concept of rationality can be challenged, for example the assumption that costs and benefits can be sensibly added up and balanced in this way. In the context of climate change, the rationality of cost-benefit analysis might be challenged on grounds of the irreversibility of the phenomenon, the pervasive uncertainties and ethical arguments. Anybody who rejects the quantified sum of climate change impacts as a basis for decision making is free to employ a different approach. But cost-benefit analysis is a coherent approach, and no more is required by decision analysis. Anyone who wishes to follow this concept of rationality can use cost-benefit analysis as a means to assess the consequences of a coherent application of this rationality concept. This can be done as demanded in the second requirement:

2. Employ calculus to check thoughts for coherence

The use of calculus to bring very different aspects into one coherent model is a core characteristic of cost-benefit analysis. But, contrary to traditional cost-benefit analysis, probabilities need to be the subjective probabilities of the problem owners as stated in the third requirement:

3. Reflect the values and beliefs of problem owners

As mentioned above, in this context, the definition of 'problem owners' needs to be revised. In the original concept of decision analysis developed for individual decision making or decision making in small groups, the problem owners are obviously those people who wish to make the decision or are affected by the decision. In the case of climate change, whole societies need to decide how to deal with the crisis. Practically every human being is a problem owner, both as being affected by climate change and as producing greenhouse gases. Furthermore future generations are severely affected, but can not be involved in the modeling. Therefore, this definition is too broad to be applicable here or to facilitate a focused discussion of the key issues in this chapter. Not every human being can be involved in a modelling exercise on the costs and benefits of climate change. In the following problem owners are defined to be decision makers in public policy and the experts working for them. But many results can be easily transferred to other groups of people, although not to future generations. The involvement of different decision makers and problem owners in the modeling process is further discussed below in the paragraph on the fourth requirement.

As most research about cost-benefit analysis of climate change was conducted in countries with democratic governments and structures of division of powers, the definition of problem owners can further be restricted to the responsible politicians from the legislative and executive bodies of democratic governments. This narrower definition enhances the clarity of the following analysis without giving up too much generality. Most findings can be transferred to other forms of government if necessary. Finally a further important restriction is being introduced: in the following it shall be assumed that the decision analysis model is developed with the aim to help the politician to make the best decision for humanity. This excludes two narrower motivations: neither shall the personal interest of the politician as opposed to the interest of his competitors or the general public be regarded here, nor shall the politicians' perspective be limited to impacts that accrue to people in their country only. Whether the problem owners value animals, plants, ecosystems and biodiversity only at their benefit for humans or as values in themselves shall be considered open to their own judgement. For a discussion of this definition see the box on page 95.

The definition is in line with the theoretical concept developed in Hope and Owen (1986). According to them, cost benefit analysis accepts the value judgements of the democratic decision maker as a legitimate input (p. 856). A common example would be the decision makers' preferences for distributional issues. Basically all inputs for which market prices don't exist would need to reflect the values of the decision makers.

Hope and Owen admit that this form reduces the independent economic validity of cost benefit analysis. That is, the distinction between science and politics becomes less clear, giving more power to the decision makers. Whereas amenity values derived from secondary market data or with help of questionnaires reflect the preferences of different individuals in society, there is no reason other than democratic structures why the preferences of a decision maker should be a good description of the general preferences of society. The issue is at least as difficult for the treatment of uncertainty: There is no reason to assume that the beliefs of decision makers on uncertain events or causalities should be on average more exact than those from scientists. The contrary would be more likely, as the scientists have more specialized knowledge on their field of research. Still, whenever various scientists arrive at different results or the state of the art is characterized by a high degree of uncertainty, the legitimate people to decide about the way to deal with these uncertainties are the decision makers, according to the approach above. Maybe this accumulation of power can only be justified in the light of the possibility, that all different actors in the political arena are equally entitled to test the consequences of their subjective values and beliefs on model results. Hope and Owen argue that the distinction between objective science and subjective decision making was never given for the issues discussed here, so not very much is lost anyway. But the problem remains, that a politician can not know the welfare consequences of his decisions for all individuals – and maybe doesn't even wish to decide in the interest of the whole society rather than a certain group.

Personal, national and global perspectives:

Cost-benefit analyses of social projects in general try to answer the question what is good for society, not how can politicians maximise their personal well-being. This basic concept shall be maintained here and extended to take a global instead of a national perspective. Climate change is a truly global problem that can not be solved by single countries or even continents. Fairness will be crucial to gain an understanding at international negotiations. As game theory has shown, the response to climate change is clearly suboptimal if every country considers only its own emissions and own impacts. The global perspective is therefore important for a solution and interesting to reflect in cost-benefit analysis. The global perspective has partially been adopted in international environmental law and in moral philosophy. Traditional cost-benefit analysis also takes this global perspective, although not always to the last consequence. An important example is the valuation of the risk of death of people in different parts of the world. This issue is discussed in more detail in chapter 7.2. For the definition here, the valuation can be left to the problem owner. In reality, all citizens are decision makers. We vote and are the source of all democratic power. We consume and depend on the natural resource endowment of the world. A cost-benefit analysis may help citizens in their decision making as well, if they choose to engage on entering this complex issue.

Similarly to subjective probabilities, the risk preference and other values should be those of the problem owners in a model based on decision analysis. It is tricky to accommodate the concept of subjective value functions in cost-benefit analysis, where all impacts are monetarized. They are valued at their market value or, where this is not available, retrieved with methods that try to establish what the market price were if a market existed. There is no special reason, why any single person's preference ranking of different combinations of goods should be exactly equal to the preference ranking valued in dollars through monetisation. Fortunately, the problem is somewhat alleviated by the fact that the decision makers are assumed to be public policy agents acting in the interest of society. So it is not the value function of any individual or small group of individuals that matters, but rather the value function of society – or what the decision maker assumes the value function of society to be. In reality, the personal values and opinions of a politician may sometimes play a more important role than the assumed preferences of society, but in the description of problem owners above, this egocentric point of view was defined as not relevant here (see page 94).

It is often reasonable to consider the market prices of goods as useful approximations of their values to society. Where perfect markets don't exist and the prices are therefore considered to be distorted, the problem owners should adjust the price inputs to the model according to their judgement. Where the valuation of non-market goods is necessary, again the judgement of the problem owners should define the input to the model in accordance with the presuppositions of decision analysis. It is possible, that the policy makers will object against expressing all impacts including the loss of human lives in monetary terms. This is a general caveat for the usefulness of cost-benefit analysis of climate change as a decision aide to public policy. It equally affects the traditional form of cost-benefit analysis, only that here decision makers do not need to participate in the effort of monetisation and may therefore be less aware of the corresponding difficulties. An attempt to accommodate this uneasiness could be to express the costs of climate change in more than one metric, for example monetary costs and loss of human lives. Such procedures have been suggested before, e.g. by Schneider et al. (2000). They are, however, not compatible with the basic idea of cost-benefit analysis: to list all costs and benefits in the same metric, compare the sum of these and arrive at a clear and unambiguous recommendation for optimal action. For more than one metric such an unambiguous result is only possible, when the results for all metrics lead to the same conclusion. In this case, the result would be rather strong. Specifying the impacts of climate change in more than one metric can therefore be a very valuable way to present information (cf. Stern 2007: 145).

But in the case of climate change when an optimal emission quantity is looked for, it is highly unlikely that different metrics suggest the same intensity of mitigation – even if the results for all metrics might suggest that more mitigation action than currently taken is optimal. The multi-attribute analysis then does not lead to the kind of decision aide aimed for in cost-benefit analysis.

A problem to the realization of the third requirement, representing the problem owner's values in the model, is the fifth particularity of cost-benefit analysis of climate change listed above: complexity of the task. A cost-benefit analysis of climate change is too complicated and bulky for the public decision makers to assist during all steps. It is probably unrealistic that they participate in the whole process of valuing benefits and losses caused by climate change. This touches upon the fourth requirement:

4. Develop the model in an iterative, interactive and consultative process between specialists and problem owners

A different realization of decision analysis will probably be necessary where this point is concerned. A possibility and more realistic option might be the development of a cost-benefit model in the scientific community with a clear indication of just a few contentious values that the decision makers can change in a sensitivity analysis according to their own judgement. If the model is developed in the scientific community rather than in the iterative, interactive and consultative process demanded above, this is a digression from the original idea of decision analysis. It leads to a modelling approach that resembles traditional attempts to deal with uncertainty: sensitivity analysis for a few key parameters is a common procedure for integrated assessment models of climate change (e.g. Nordhaus 2007b: 76). It is assessed whether, and if so how, the key advantages of decision analysis can be maintained with the necessary adaptations outlined in this paragraph.

A first important precondition for avoiding a false impression of objectivity would be a very open discussion in the scientific community about the values in the model. If it is not just one analyst entering his own best judgement, but rather a range of scientists discussing the settings in the model, contentious variables are more likely to be identified. If discussion can not resolve the disagreement in the scientific community, these inputs should be left for the decision makers to set, or a range of different values should be entered into the model. If the participating scientists are from diverse backgrounds, it might be assumed, that their compound judgement is close enough to that of society to make the model a useful decision aide for public policy. If all participating scientists come from the same discipline or the same scientific institution, however, a form of group bias can easily occur. They will all judge certain aspects of the problem from a similar angle, and may omit the existence of other values and beliefs in society.

As long as the decision makers, or at least the experts in the decision-making bodies, have the possibility to check the credibility of the model and adapt it in key aspects so as to become credible to them, the objective of decision analysis can partially be safeguarded. This objective was given above as to allow “the decision maker to use the model as an aide to structure ideas and thus reach a coherent decision based on his or her own values”. A drawback exists to the realization of this objective in a cost-benefit model developed as described above: it structures mainly the ideas and knowledge of the scientific community, not of the decision makers. This is critical whenever the assumption from above holds, that not all subjective inputs like normative settings and judgments on uncertain inputs can be clearly separated from the modelling and left for the problem owners to specify.

To a certain extent, the discussion between different scientists replaces the democratic discussions, which lead to the election of certain decision makers. This may even be an advantage, as the public discussion can not be led at the same level of detail and with the same depth as the scientific discussion. But the danger of scientists gaining more power than their democratic share is not easily eliminated with such an approach. The advantage hinges closely on several assumptions: First, that a diverse number of scientists are involved in the iterative and consultative process of building the model; second, that the public has not in general values that differ from those of the scientists; and third, that the contentious issues are clearly marked and left for sensitivity analysis.

Another possibility for scientific model builders to avoid a false impression of objectivity would be the use of ranges or probability distributions as inputs instead of point estimates. In this case the result is also a range or probability distribution, not a point estimate. This indicates clearly that the uncertainty can not be objectively dispelled by the analyst. However, even these ranges of uncertainty are subjective, as the upper and lower bounds as well as the form of the probability distribution functions for the inputs need to be chosen.

The next requirement above is given as:

5. Use problem owner's sense of unease to improve the model

This requirement is not easily fulfilled for a cost-benefit analysis of climate change, as it requires rather far-reaching influence of the problem owner on the model structure. More than the adaptation of a few contentious input variables may be necessary to accommodate a sense of unease by the problem owner; maybe a decision maker feels uneasy about the concept of cost-benefit analysis itself, and rather wishes to adopt a tolerable window approach or undertake a multi-attribute analysis in which not all impacts are converted into a monetary metric. But, similar to the discussion under requirement three, this criticism would lead too far here. The decision maker might also disagree with the rationality concept of decision analysis. He or she would be free to use any other aide for decision-making. Decision analysis is just a possibility, although proponents argue a rather sensible one (cf. Watson and Buede 1987: 12). Equally decision makers are free to reject the information that cost-benefit analysis provides. But in order to embark on any meaningful discussion about the concept, an agreement from the politician's side to accept a subjective form of cost-benefit analysis as an interesting tool to aide decision making needs to be taken as granted.

Still, the requirement that the problem owner's sense of unease within the structures of cost-benefit analysis shall be employed to improve the model is a rather ambitious one. It requires a good understanding of the model by the problem owner and either easy possibilities to adapt the model or a very good communication between the problem owner and the modeller.

Requirement six remains to be assessed in this context:

6. Check goals as well as the best way to achieve a given goal.

In cost-benefit analysis the goal is usually prescribed: to identify the path with the highest overall welfare for society. If goals are checked as well as the best way to minimize the combined costs of climate change impacts, mitigation and adaptation measures, this clearly leads outside the structure of a cost-benefit model. But in the sense that the welfare valuation and comparison of different states of the world is at the centre of interest, this valuation is one of the core tasks of cost-benefit analysis. Cost-benefit analysis could be described as a tool especially to help think about a goal, not just the way to reach a given end: it provides information on how much mitigation and adaptation measures are wise to take, which final greenhouse gas concentration in the atmosphere should be envisaged as a goal not to be exceeded. Therefore requirement six is regarded as no obstacle to the realization of decision analysis to cost-benefit analysis of climate change.

The further requirements,

7. Simplicity
8. Open and easy access to all the details of the model,

follow from the central aim of decision analysis and the discussion above. The model needs to be sufficiently simple for the decision maker to understand it. This need for simplicity exists for every model based on decision analysis. But the requirement receives a new importance, when a cost-benefit model is developed by scientists and politicians make the decisions. The split into specialists who provide the form and problem owners who provide the content is a common feature of requisite decision models as described by Phillips. Ideally in the case of climate change, experts should give all the confirmed knowledge that can be treated as quasi-objective, and decision makers should choose all subjective inputs. However, cost-benefit analysis of climate change being a very complex task and politicians having a limited time budget, in this case it may be necessary that much of the development of the model takes place in the realms of science, as described above. Even within the scientific community a profound discussion of the model among scientists with diverse backgrounds will only be possible, if the model maintains a sufficient simplicity. This is even more relevant for the political sphere. The contentious issues will remain for the decision makers to enter their own beliefs and values. They don't need to understand every detail of the maths behind the model, but enough of the content and structure, to gain new and reliable knowledge and understanding from using the model. The model will basically provide information of the type "if the assumptions and values are set as in the model, then the given result follows rationally". The decision makers need to understand the structure and content of the model in order to be able to judge whether they wish to accept the "if … then" statement as true. For a cost-benefit model of climate change this could mean, that at least the experts in the legislative and executive bodies should be able to check whether or to what extent they agree with the model structure and assumptions. For this, simplicity is especially important. The last requirement is a direct consequence hereof: if the experts are to check the credibility of the model, all necessary information needs to be published and easily accessible.

To sum up the applicability of decision analysis to cost-benefit analysis of climate change, the following conclusions can be drawn: Due to the complexity of the task and the limited time budget of decision makers, most of the model development will necessarily take place in the realm of science. This entails the risk that the subjective valuations of scientists are represented in the model without decision makers realizing the fact. The danger is reduced when

- scientists from diverse backgrounds participate in the model development
- the model is sufficiently simple for peer review to be effective and for decision makers to understand structure and content
- the scientific debate on the model is organized for example in conferences, to assure a thorough check before using the model
- contentious inputs are clearly indicated for the decision makers to compare the standard settings to their own beliefs and, as the case may be, to adapt the values.

The usual procedures of decision analysis can not be applied to cost-benefit analysis one-to-one. It depends on the realization of the four bullet points above as well as the dedication of the political decision makers, whether decision analysis can be reasonably well reflected in cost-benefit analysis of climate change. Taking into consideration the adaptations and changes to the theory suggested above, it is theoretically possible to capture the main ideas of decision analysis in cost-benefit analysis of climate change. This is, however, no easy task to undertake. Although requirements 1, 2 and 6 will be no problem, the requirements 3, 4 and 5 are not easily accommodated in cost-benefit analysis. Requirements 7 and 8 are especially important in this context.

Realization of the principles of decision analysis in the cost-benefit model PAGE

5

In the last chapter, the theoretical possibility of applying decision analysis to cost-benefit analysis of climate change was assessed. In the following, the practical realization of this endeavour in the model PAGE is examined.

As described above, the critique of the way to deal with overwhelming uncertainties in cost-benefit analysis of climate change was the motivation for the endeavour to try and apply decision analysis to the PAGE model. The main point of the critique was that uncertainties falsely appear to have been dealt with objectively in major cost-benefit models of climate change, although they can not be resolved objectively through scientific research either in principle or at this state of research. It was claimed that the subjective valuation of the modeller substantially influences the result, but that this subjective influence is not openly admitted and flagged – although the subjective valuation of the decision maker may be quite different of the values used in the model.

As a consequence of this criticism, the cost-benefit analysis model PAGE is based upon the theory of decision analysis, which has been outlined in the paragraphs above. It was also shown, that the application of decision analysis to cost-benefit analysis entails some difficulties. In the following, the implementation of this theory in PAGE is analysed. The hypothesis for this analysis is the following:

Hypothesis 2: To avoid a false impression of objectivity and certainty, decision analysis was chosen as the theoretical foundation for the integrated assessment model PAGE. But although the model PAGE is not subject to some of the common problems in dealing with uncertainty, it does not live up to the standards of its underlying theory: decision analysis.

5.1 The PAGE model

A detailed description of PAGE2002 can be found in Hope (2006) and Hope (2008a). PAGE is an integrated assessment model containing

- emission assumptions from the A2 scenario of the IPCC's special report on emission scenarios
- sulphate aerosols emissions and assumptions about feedback mechanisms of global warming on natural greenhouse gas emissions
- a representation of warming caused by the greenhouse effect and cooling caused by sulphate aerosols
- a representation of impacts of climate change in three sectors: market impacts, non-market impacts and large-scale discontinuities
- assumptions about the benefits of adaptation.

5.2 Easy access to the model

As a detailed description can be found in the literature, PAGE fulfils the eighth requirement above: open access to all the details of the model. Furthermore, the model is built in the commonly used software Excel with the use of an add-on software for the Monte Carlo analysis. This add-on software is available on the market and very easy to use. Most scientists today frequently work with or have worked with Excel and have no problems handling the program. PAGE can be obtained from the model builder Chris Hope free of charge for academic purposes. It is therefore reasonably easy for other scientists to get the model running on their own computers.

This is not the case for all integrated assessment models. For example, the access to the integrated assessment model FUND is more difficult. Although formulas and parameters are published on the internet and in journal articles, the understanding of the model from the literature is very time-consuming. Information from different journal articles needs to be combined to understand the most recent version of the model. This is true although a description of the model is available on the homepage, as the description of the model is very brief and the development of the input parameters is not explained there. Although a version of FUND is available on the homepage, it is not possible to use it without a software that is no longer available on the market and not widely used. Another software is indicated on the homepage as a possible alternative. But the denomination is ambiguous, and internet research by the author led to no result. Other scientists who wish to assess the qualities of FUND from their point of view encounter difficulties.

Even easier to access than PAGE is the DICE model from William Nordhaus: both versions for the software GAMS and the software Excel are available on the internet and all details are published in a structured form in books, articles and on the internet.

5.3 Simplicity

The better accessibility of PAGE and DICE compared to FUND is only partly the consequence of easy-to-use software and clarity in the publication of the results. FUND is also the more complex model, e.g. relying on a wider range of studies for the representation of impacts (see chapters 2.1 and 2.3). Different opinions may be held which approach is the more suitable one. Climate change and the impacts thereof are very complex issues, therefore a simple representation must miss out on important aspects. On the other hand simplicity reduces the danger of errors and makes it easier for the user of the model to interpret the results of the model adequately. William Nordhaus started the description of his 2007 update of DICE with the following quote by Leonardo: "Simplicity is the highest form of sophistication." (Nordhaus 2007b: 2)

Whether or not cost-benefit analysis of climate change with the traditional approach striving for objectivity is best effectuated with a complex or a simple model need not be resolved here. Clearly, for a model based on decision analysis, simplicity is a necessary virtue. This was explained above, as simplicity is actually the seventh requirement that was formulated for the application of decision analysis to cost-benefit analysis of climate change.

PAGE is a simple model in most aspects (cf. Hope 2006: 21) – even very simple in some parts like the representation of impacts and the regional differences in temperature rise. Hope justifies this simplicity with the remark, that the results approximate real-life conditions sufficiently well. This seems to be true at least for the climate module of PAGE: the increase in CO_2 forcing per year is remarkably close to the results from the IPCC Third Assessment Report, which are based on much more complex calculations (Hope 2006: 28).

Still, the scope for simplicity in any assessment of the complex phenomenon climate change is limited. If PAGE is described as a relatively simple model, this judgement must be seen in this context.

5.4 Stakeholder participation

In the previous sub-chapter it was shown that PAGE complies comparatively well with the requirements seven (simplicity) and eight (open and easy access to the model) from the list given in the chapter about decision analysis. In the general chapter about the applicability of decision analysis to cost-benefit analysis, it was explained that the requirements one (a concept of rationality), two (employment of calculus) and six (scrutiny of goals as well as ways to get there) of decision analysis as given above are inherently accommodated in cost-benefit analysis. Therefore requirements three to five remain to be looked at. They can be subsumed under the heading "stakeholder participation". The requirements are

3. reflect the values and beliefs of problem owners
4. develop the model in an iterative, interactive and consultative process between specialists and problem owners
5. use problem owner's sense of unease to improve the model

As explained above, these demands can hardly be met one-to-one in a cost-benefit model of climate change. In the following, it is assessed how this challenging task has been dealt with in PAGE2002.

First, the application of requirement four is assessed: PAGE, like other major integrated assessment models, has been iteratively improved. Earlier versions of the model exist and a new version is being developed at the moment. These changes to the model are among other factors inspired by comments from colleagues. This is, however, in itself no justification for the claim of complying with decision analysis. It is the normal scientific procedure to publish details about a model and take critique from the scientific society into account while preparing an improved version.

The requirement is to improve the model in an interactive process between the modeller and the problem owners. So, even if the policy makers can not assist during the whole process of model building as explained above, they should at least be able to recognize the most important contentious points and be able to assess the model outcome with their own subjective settings.

In this context it is interesting that PAGE was taken as a basis for the Stern review, a report about the economics of climate change commissioned by the British government. Nicholas Stern, then Head of the Government Economic Service (*Stern team*), and his team undertook among others the task, to review the results from PAGE under additional or changed ethical assumptions. An addition to the model called DYNASTY was developed, in which these new assumptions were realised. Examples are the value of damages in the near and far future. In the following these two changes to the original subjective settings in PAGE are explained:

Valuation of impacts into the far future: In PAGE, the value of impacts is taken into consideration only until 2200. Greenhouse gas emissions today and in the future are assumed to have no influence on the world after 2200. Nicholas Stern, during his work commissioned by the British government, adapted the model so as to allow for damages to be felt after 2200 – in fact, to be felt into perpetuity. It is no straightforward procedure to quantify the value of losses forever. Therefore, the assumption can be and has been criticised. For example, Nordhaus (2006: 12) and Tol and Yohe (2006: 239) claim that, due to Stern employing a very low rate of pure time preference, the damages in the model after 2200 are disproportionally high. The rate of pure time preference is essentially a measurement of impatience. It is clearly a subjective input to any model of cost-benefit analysis. Therefore it is interesting, when such a subjective setting introduced by a project initiated by political stakeholders leads to a result very different from previous scientific work. However, the formula accommodating the impacts after 2200 is rather complicated and probably beyond the scope of policymakers to validate whether its meaning is consistent with their subjective beliefs. This is problematic as the part of the model describing the time-horizon beyond 2200 has an important effect on the final result.

Stern defends his model settings as conservative, that is according to him climate change impacts are likely not overestimated. His argument builds upon the fact that he only allows for the valuation of damages that have occurred until 2200 for the time thereafter. Even in the settings of Stern, no new damages are assumed to accrue after 2200. For example, if land is lost due to sea-level rise, Stern assumes that the land lost until 2200 would have had a value after 2200 as well – and this value is reflected in his model. But he does not assume that additional land is lost after 2200 due to a further rise of the sea level. This is clearly unrealistic, as sea-level rise is a very slow process that can take centuries to millennia, even after greenhouse gas concentrations have been stabilised (Watson et al. 2001: 17).

This controversy shows that the question of impacts after 2200 is one of the points, where no objective, final answer from science exists. Here, one of the principles of decision analysis above has been effectuated in reality: Scientists and policymakers involved in the Stern team have used their sense of unease about impacts after 2200 being ignored in the model to adapt the calculations.

General valuation of impacts in the future, including the near and mid-term future: Discounting, that is the valuation of benefits and losses in the future compared to today, has long been one of the most contentious issues in cost-benefit analysis of climate change (see for example Al-Nowaihi and Dhami 2008; Azar and Sterner 1996; Blackorby et al. 2000; Dietz et al. 2008; Guo et al. 2006; Lind 1995; Neumayer 1999; Rabl 1996: 137f; Schelling 1995). One of the key changes to cost-benefit analysis in the Stern Review is a different approach to discounting than previously used in these models. Usually, a discount rate is chosen and applied to the entire model period. Some authors have suggested to use different discount rates for the near and the long term (e.g. Rabl 1996: 138f). But Stern claims that climate change is a non-marginal incidence, that is that the impacts of climate change have a notable influence on economic growth, and that therefore the discount rate has to reflect this influence (Stern 2007: 27). This reasoning goes back to the so-called descriptive approach of discounting, which has been widely used (for example in the literature cited above). According to this approach, the discount rate (d) is made up of two parts: the pure rate of time preference (p) and the economic growth rate (g) multiplied by the negative of the elasticity of the marginal utility of consumption (η):

$$d = p + \eta \cdot g \tag{5.1}$$

According to Stern, the appropriate discount rate can not be chosen prior and independent of the impact valuation, as these impacts have a significant influence on economic growth and therefore on the discount rate. In his adaptations to the PAGE model in the add-on DYNASTY, such a different discounting approach is realised. Only the pure rate of time preference is applied according to traditional discounting calculus. The effect of the marginal utility of consumption being dependent on the overall level of consumption is considered via a new approach, where the modelled level of consumption with climate change is the basis of the utility calculation rather than a theoretical growth rate. So again, commissioned by a political body involved in public decision-making, new subjective assumptions were introduced to better reflect the point of view of the problem owners.

These two examples show that a similar approach as demanded in the requirements 3 and 5 above has been applied to PAGE in the Stern review. Taking into account the difficulties of involving political decision makers in the process of developing the model, this was a far-reaching attempt on behalf of the British government to accommodate different subjective ethical assumptions and beliefs in an existing model. It is true, that the realization and also the identification of controversial subjective assumptions were effectuated by Stern and his team. Stern was working for the British government as Head of the Government Economics Service unit while he was in charge of the review, but his views may still differ even from those of members of the government who commissioned the review, let alone other decision makers in Britain and all over the world.

The example illustrates once more the great difficulties of involving problem owners in the model construction. Major changes are so complicated that experts are needed to effectuate them in the model – and it is hardly feasible that every interested problem owner commissions such a work. Minor changes that affect only the setting of one or two parameters, on the other hand, can be made for different values of these parameters. This was for example done in the Stern Review for different values of the pure rate of time preference and different values of a parameter called η, the negative of the elasticity of the marginal utility of consumption (Dietz et al. 2007: 319). In the Stern model this parameter denominates risk aversion, and elasticity of the marginal utility of consumption both for levels of income across time and across space. Policy makers can thus quickly appreciate the influence of different settings of these parameters on the final result. However, even to fully capture the concepts of these parameters quite a level of expertise is necessary, so that this knowledge is only available to the informed decision makers with economic knowledge. And sensitivity analysis is a common concept in science, not a particularity of decision analysis.

Furthermore, even in the quite extensive work of the Stern Review, not all sense of unease could be accommodated in the model adaptations due to time constraints. The combination of PAGE and DYNASTY is not a requisite decision model as described by Phillips. For example, Stern himself suggests that the integration of equity weighting into the results of the Stern Review would have improved the quality of the work (Stern 2007: 163). The results in the Stern Review incorporate only a very rough estimate for equity weighting: that damages are assumed to be about 40% higher when allowing for spatial equity considerations (Stern 2007: 163). A lot more contentious issues remain that could not be worked on in detail in the Stern review, as for example the impact parameters.

The publication of the Stern Review and the following public attention on the model led to further discussion of PAGE in the scientific community. For example at the Yale Symposium on the Stern Review in February 2007, ten scientists with a background in cost-benefit analysis of climate change discussed the modelling in the Stern Review including the assumptions of PAGE (Yale Center for the Study of Globalization 2007). Chris Hope, the modeller of PAGE, invited all participants to run the model with different parameter settings of their own, if they disagreed with the original assumptions. In general, the parameter choices in PAGE were accepted as reasonable, or at least as not unduly overestimating climate change impacts, as had been expected by some participants in the beginning.

Before the publication of the Stern Review, the offer to the scientific community to use PAGE and enter different parameter values was already given. The model is conceived to be a tool to explore the consequences of subjective values and beliefs of different people, not just the model builder. However, this did not frequently happen. Even though PAGE is a rather simple model, effort is needed to understand it well enough to meaningfully change parameters. Even the Stern team made almost no changes to the original PAGE model, but just developed an additional add-on to further improve the results from PAGE according to their ethical assumptions. The details of DYNASTY are not explored here beyond the explanations above, as this is beyond the scope of the dissertation.

Thus, requirement number four (and consequently requirements number three and five as well) to develop the model in an interactive and iterative process was envisaged by the model builder Chris Hope. It was realised to the extent that later model versions incorporate comments from the scientific community on earlier versions. The invitation to change model parameters wherever other values are preferred was openly given. But the occurrence of other people actually changing parameter values according to their own beliefs was limited. Partly this is due to the comparatively large effort of determining an opinion on the best parameter settings in the model. Where other people checked the input as was done at the Yale Symposium, they did not think other values were palpably more suitable than those originally used in PAGE.

Where possible, these parameter settings are based on the work of the Intergovernmental Panel on Climate Change (IPCC). The publications of the IPCC have a high authority, as they are based on a very profound and global discussion of the state of the art. During the formulation of the summary, even government representatives are involved. The IPCC process may therefore be described as a special realization of decision analysis in the science of climate change: scientists provide the best knowledge available, and governments safeguard that the beliefs and values of the political decision makers are not passed over. It is therefore entirely rational for decision makers to accept these numbers as the best foundation for integrated assessment modelling. However, as the IPCC may only publish policy-relevant knowledge, but not policy-prescriptive advice, many of the questions where decision analysis would be most interesting to use are not embraced in the IPCC process. It is in the nature of policy advice and the decision making for political action that ethical values and beliefs play a very important role.

5.5 Probabilistic approach

The stakeholder participation approach of decision analysis was not the reason Stern based his calculations on the model PAGE. Stern and his team looked at several integrated assessment models and chose PAGE for their work mainly because of the probabilistic structure of the model (Stern 2007: 153).

As described above, decision analysis was chosen as the foundation of PAGE mainly because of the criticism, that the uncertainties in cost-benefit analysis of climate change are very large and that subjectivity can not be avoided. In PAGE, one way of dealing with these huge uncertainties is through the application of probability distribution functions as inputs for key parameters rather than point values. With Monte Carlo analysis, these probability distribution functions can be included into the model calculations, and the model results are equally given as probabilities, not exact results. PAGE thus offers additional information compared to a deterministic model that works with best guesses and not probability distribution functions. Decision makers from the policy arena can consequently base their actions upon both likely impacts of climate change as well as risk considerations. Concerning the important ethical questions of risk aversion and the application of the precautionary principle, it is therefore easier for decision makers to consider the conclusions that follow from their own values, rather than be faced with fixed settings in the model.

Unfortunately, this additional information is not always perceived in the political arena. For example, in the Stern review 95% probability intervals were reported as well as best guess values (Stern 2007: 163). But in the media and the public discussion the best guess values have dominated the debate. However, it can be assumed that at least the experts in the governmental decision making bodies do have an understanding of risk and probability and can use the additional information offered by the probabilistic approach.

In PAGE2002, 31 parameters are represented by probability distribution functions. Examples are the equilibrium warming for a doubling of CO_2-concentrations, the exponent of the impact function describing the correlation between temperature rise and growing impacts, or the tolerable warming before the danger of a large-scale discontinuity sets in. Figure 5.1 shows the corresponding probability distribution functions that are effectuated in PAGE2002.

A few different assumptions concerning the discount rate and equity weighting have been explored (Hope 2008a: 1014ff). The model was recalculated with different point values for the discount rate and equity weighting. In recent applications modelers have usually treated the two input factors as uncertain variables using probability distribution functions. However, the probabilistic approach is a better method to deal with uncertainties than with ethical assumptions. For the main ethical assumptions, which are limited in number and entirely subjective, the most straightforward way to address them is to allow policymakers to explore the consequences of their own judgement in a sensitivity analysis.

In DYNASTY, the discount rate is different, based upon a thorough realisation of the prescriptive discounting approach. It is indirectly probabilistic, as it depends on the impacts of climate change calculated in the model – which is based on the 31 probabilistic input parameters.

5.6 Practicability of using PAGE as a tool according to decision analysis

In the previous subchapters, it was described how the principles of decision analysis are envisaged in PAGE. For this purpose, all the principles were individually checked with an appraisal of how it was attempted to realise them in PAGE and whether this is in line with the claims of the theory. Some details of PAGE were already looked at during this appraisal, but on the whole it was a check whether the approach of PAGE is in line with the theory of decision analysis. In the following, not just the approach, but the content of PAGE is assessed against the claim of decision analysis: Can problem owners realistically judge their level of agreement with the parameter settings in PAGE?

If not many changes in parameter settings were suggested from peers, this may be the case because they mainly agree with the original values in PAGE. Some parameters rely on the publications of the IPCC. For others, such an authoritative source is not available, but they may still be reasonably chosen. So the lack of more intensive interaction between the modeller and the problem owners can not in itself be taken as a proof that PAGE does not fulfil the basic purpose of a model based on decision analysis: to allow decision makers to use the model as an aide to structure ideas and thus reach a coherent decision based on their own values.

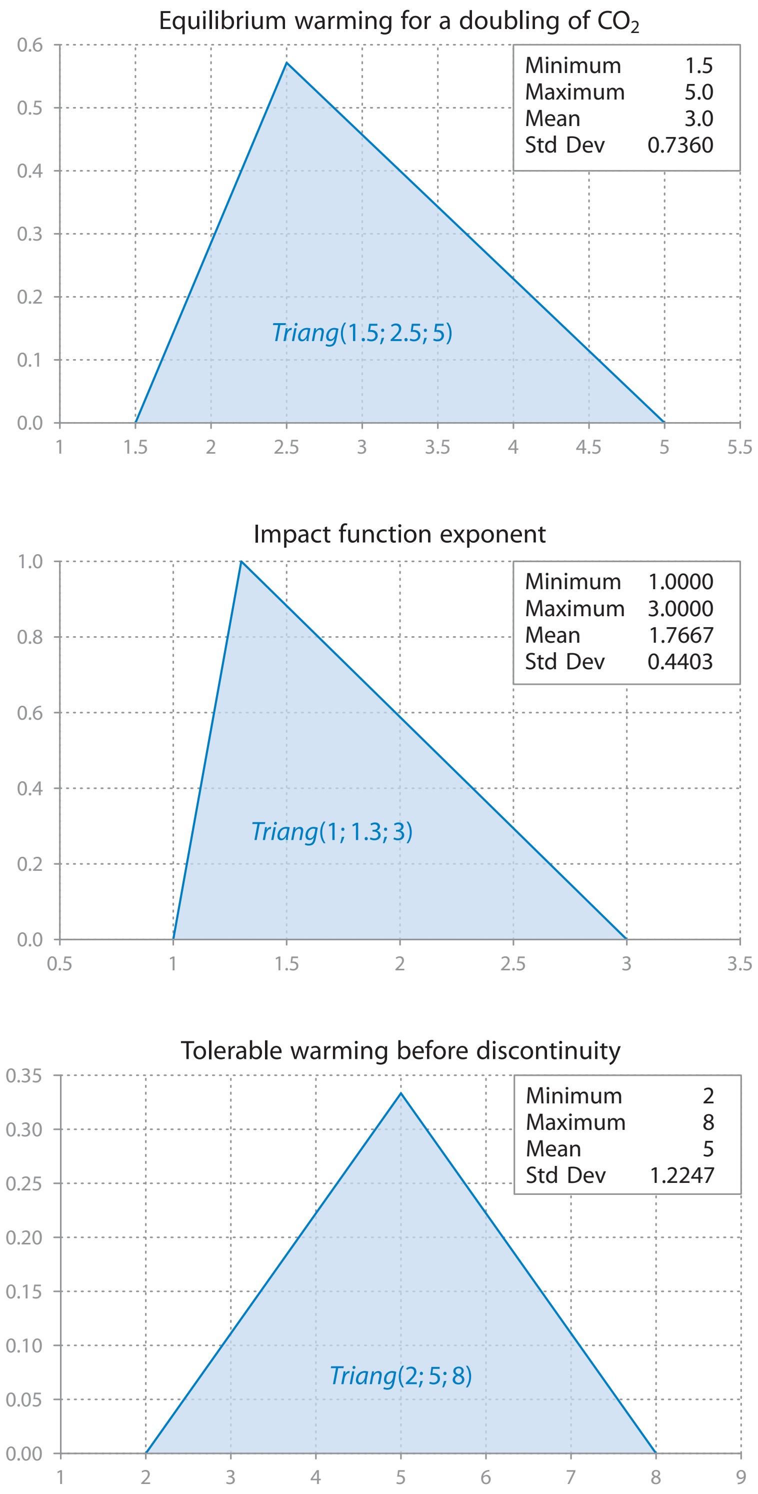

Figure 5.1: Examples for probabilistic inputs to the PAGE model

So what are the chances for a political decision maker to judge his level of agreement with the subjective assumptions in the model? It is assumed that the scientific rigidity of the model calculations is safeguarded through scientific peer review. The problem owner need not check the whole model, but rather understand the contentious uncertain inputs and the ethical assumptions. As described above, only specialists within the political governments can be supposed to have time and expertise to identify and question model assumptions. This is inevitable for such a complex task. In the following, the practicability of specialists identifying the relevant subjective assumptions and developing a proper opinion shall be assessed.

5.6.1 Socio-economic data

The socio-economic data in PAGE are taken from the A2-scenario of the IPCC special report on emission scenarios. The underlying assumptions are well documented (Nakićenović and Swart 2000). It can therefore be assumed that any specialist trying to judge his or her level of agreement with these parameter settings has the possibility to do so.

5.6.2 Ethical assumptions

The discussions about the correct discount rate and equity weighting are long and controversial. The only possibility to openly deal with the issue is to be very clear about the assumptions and illustrate the consequences of different assumptions in these categories. This has, at least for a small range of numbers, been done in Hope (2008a: 1014ff) for the discount rate and equity weighting. Other assumptions for these two parameters can be tried comparatively easily, if a problem owner wishes to do so.

5.6.3 The climate module

The representation of the greenhouse effect in the atmosphere and the consequent warming are closely based on IPCC publications, and can therefore be accepted as sound science. Some of these inputs are given as probability distribution functions because of the large uncertainties. Mostly the Third Assessment Report is the basis for PAGE2002.

One parameter that has lately sparked scientific discussion is the equilibrium warming for a CO_2-doubling (Meinshausen 2006; Weitzman 2009: 1f, 8f). An excursus shows the effect of different uncertainty assumptions as reported in Weitzman (2009: 5f) on the final impact result in PAGE.

Excursus: Sensitivity analysis with respect to the warming for a CO_2-doubling

Weitzman (2009: 8f) suggested that an appropriate probability distribution function describing the scientific knowledge about climate sensitivity may be fat-tailed, or indeed very fat-tailed. He thus suggests that the probability of high values materializing is declining slower than the values are rising towards the right side of the probability distribution function. Therefore the product of value times probability is not declining for high values. In line with this suggestion of a fat-tailed probability distribution function, a lognormal probability distribution function is chosen. The parameters defining the lognormal probability distribution are designed to fit the description of likelihood from the IPCC Fourth Assessment Report. There it is written:

> Analysis of models together with constraints from observations suggest that the equilibrium climate sensitivity is likely to be in the range 2°C to 4.5°C, with a best estimate value of about 3°C. It is very unlikely to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement with observations is not as good for those values. Probability density functions derived from different information and approaches generally tend to have a long tail towards high values exceeding 4.5°C. Analysis of climate and forcing evolution over previous centuries and model ensemble studies do not rule out climate sensitivity being as high as 6°C or more. [. . .] The lack of strong constraints limiting high climate sensitivities prevents the specification of a 95th percentile bound or a very likely range for climate sensitivity. (Solomon et al. 2007: 65).

The significance of the descriptions of likelihood in the IPCC Report are given in table 5.1.

No lognormal probability distribution function was found that exactly fits these descriptions. The analysis by the IPCC suggests a probability distribution function with a long tail rather than a thick tail, but knowledge on this point is not yet conclusive and the suggestion from Weitzman that a thick tailed probability distribution function is appropriate can not be ruled out on this basis. Due to this different assumption about the general form of the probability distribution function, no parameter settings for a lognormal probability distribution function were found to capture all the statements of likelihood given in the description by the IPCC. Still, a lognormal probability distribution function with the mean $\eta = 3.2$, a standard deviation $\sigma = 1.5$ and a shift of 0.1 to the right is a reasonably close approximation of the likelihoods indicated in the IPCC Fourth Assessment Report. In table 5.2 the probability of different values in this lognormal distribution are compared to the descriptions of likelihood from the IPCC Fourth Assessment Report.

Likelihood Terminology	Likelihood of the occurrence/outcome
Virtually certain	> 99 % probability
Extremely likely	> 95 % probability
Very likely	> 90 % probability
Likely	> 66 % probability
More likely than not	> 50 % probability
About as likely as not	33 to 66 % probability
Unlikely	< 33 % probability
Very unlikely	< 10 % probability
Extremely unlikely	< 5 % probability
Exceptionally unlikely	< 1 % probability

Table 5.1: Terminology used in the IPCC Reports to describe likelihood. Source: Solomon et al. (2007: 23)

The probability that climate sensitivity is	Lognormal distribution, $\eta = 3.2$, $\sigma = 1.5$ and shift 0.1	IPCC estimate
< 1.5 °C	5.1 %	5 – 10 %
2 – 4.5 °C	65.4 %	66 – 90 %
Best guess value	2.5 °C	3 °C
≥ 6°C	5.5 %	Can not be ruled out

Table 5.2: Comparison of the lognormal distribution chosen to quantitative knowledge from the IPCC Fourth Assessment Report (Solomon et al. 2007: 65)

For sensitivity analysis, this lognormal distribution is integrated as the description for climate sensitivity into PAGE. The overall impact estimate rises by 40% compared to the original triangular probability distribution function.

Weitzman practically predicted a utility of infinity for a lognormal, fat-tailed probability distribution function for climate sensitivity and a risk averse utility function. In the sensitivity analysis here, the impacts do not explode to a very high level. This is because in PAGE2002 there is no utility function that converts consumption into utility. Therefore the above result is no empirical evidence against the position by Weitzman (2009) as described above. The increase in impacts of 40% for the lognormal distribution shows the significance of the parameter for climate sensitivity, but also a notable stability of the model for changes in this single parameter. A difference of 40% is significant, but not devastating in face of the overall uncertainties involved in the calculations. In fact, it is the charm of the modeling approach of PAGE that such sensitivity analysis including the comparison of different forms of probability distribution functions is easily possible.

5.6.4 Impact representation

From the point of view of decision analysis, the weak element of the model is the impact representation – where the practicability of others to judge their agreement with the model settings is concerned. As described above, the impact representation is a very difficult part in every integrated assessment model of climate change. In PAGE, three impact categories exist: economic impacts, non-economic impacts and large-scale discontinuities. Furthermore assumptions about damages avoided through adaptation are incorporated.

The chance of large-scale discontinuities is very difficult to measure and value and is therefore only very insufficiently represented in most integrated assessment models (Downing and Watkiss n.y.: 11). In PAGE, when a certain probabilistic threshold temperature between 2°C and 8°C, most likely value 5°C, is exceeded, the danger of a discontinuity sets in. The probability of such an event is again probabilistic – between 1% and 20%, most likely value 10%, per °C that the threshold temperature is exceeded. The loss, if a discontinuity occurs, is between 5% and 20% of GDP, most likely value 10% of GDP. This is a very rudimentary and to a certain extent ad hoc inclusion of discontinuities. Due to the very high uncertainties of the assumptions, it seems hardly advisable to build a decision on the numerical outcome of this impact category alone. However, a crude representation appears better than to completely ignore an important impact category due to lack of better data. It is interesting as an addition to the calculations for the other impact categories, where some more knowledge is available. And the feature is simple enough for problem owners to have a chance to make up their minds what kind of treatment of possible discontinuities they find appropriate.

Similarly, adaptation is difficult to predict and few reliable numbers exist (Adger et al. 2007: 719). In PAGE, for each time slot in the model and each region, an assumption was made which proportion of damages will be avoided through adaptation. The default values in the model are percentages rising over time up to 50% for developing countries and 90% for industrialised countries in 2020 and remaining stable thereafter. For non-market damages, adaptation is assumed to be more difficult and the default value is set to avoid 25% of the damages from 2020 onwards. No adaptation is assumed for large scale discontinuities. The concept further includes assumptions about tolerable levels of climate change before damages result from climate change, and the tolerable rate of change which does not lead to damages. The concept is therefore not extremely simple, but an expert could understand the calculations and the parameter settings. Whether problem owners can be expected to form an opinion about the adequate values for these parameters, is a different question. It is impossible to develop an objective, but still difficult to develop a subjective number for the percentage of damages that can be avoided through adaptation in general, without any further information on the type of damages other than whether they are market impacts or non-market impacts. Still, it is an advantage of PAGE that problem owners can change all the default values and use other figures that appear most plausible to them.

The most problematic parameters in PAGE are probably the probability distribution functions both for the market and non-market sectors damages for a 2.5°C warming. Default values for market impacts are for example in Europe between a 0.1% of gross domestic product (GDP) gain and a 1% GDP loss, most likely value a loss of 0.6% of GDP. Non-market damages are between 0% and 1.5% of GDP, most likely value 0.7% of GDP. Other values apply for other regions. As the source, a table from the IPCC Third Assessment Report is given, but this is a list of results from diverse studies that are difficult to interpret.

5.6.5 Summary of findings on the model content

The assertion is ventured, that even experts from a political body or peer scientists can hardly form a subjective opinion on the likelihood of the percentage of GDP lost due to a 2.5°C warming. And the studies cited in the IPCC report rely on a wide range of subjective assumptions that are indiscernible from the table. This is more problematic for the impact numbers than for the parameters describing the chemistry and physics of the atmosphere, which were equally taken from the IPCC and which are very closely reconstructed in PAGE2002. Although these atmospheric processes are also subject to considerable uncertainties, these are small compared to the uncertainties that are hidden in the impact results and amplified by ethical choices (cf. Hohmeyer 2001: 30). For any set of probability distribution functions, the contribution to uncertainty of the different parameters can be tested in the PAGE model. For the default values, the uncertainty in atmospheric processes is given to be about the same size as the uncertainty in impact parameters. However, this reproduces only the effect of the range of possible values chosen on the final result, not the uncertainty in defining the range. Here the underlying literature is a lot more precise on atmospheric processes than on impact numbers, as can for example be seen in the IPCC Assessment Reports.

The opaque treatment of subjective input to these values in rational choice models was strongly criticised as inadequate by scientists advocating decision analysis. As a response, decision analysis was chosen as a theoretical foundation for PAGE. But relying on results from other integrated assessment models of climate change, the criticised opaque treatment of subjectivity enters the model virtually through the back door. Of course model users can use different parameter settings than those in the default version, but little information is available on realistic damage assumptions.

It was mentioned before that impact representation is very difficult. Amendments for the difficulties need to be made and the best available solution chosen. Then the problem owners may judge whether they deem integrated assessment models of climate change an appropriate decision aid – or whether they do not wish to employ such models in light of the difficulties.

The difficulty of forming a sound subjective opinion on the best values to be used, with which the problem owner feels comfortable, is partly due to the high aggregation in just two sectors apart from the discontinuities. The concept of "market damages" and "non-market damages" are rather abstract, or at least too aggregated to facilitate a subjective idea of the likely magnitude of the damages, even as an expert. Similarly, if the problem owner wishes to draw upon scientific input and studies on the subject, only integrated assessment models provide numbers on the aggregated market and non-market impacts – with all their inherent and hidden subjectivities. It might be easier for problem owners from the political sphere to form an opinion on impacts in single sectors, like impacts from sea-level rise, impacts from increased storm intensity and likelihood, and so on. Even for these less abstract categories, impact valuation is extremely difficult – but at least the numbers can be based on some concrete figures, like the expected amount of land lost due to sea-level rise. The problem owner can still doubt those numbers, but the possibility to intellectually capture the uncertainties and biases in the numbers is considerably better.

On the other hand such a detailed treatment of single sectors would enhance the complexity of the model. It remains to be tested, whether a sector-specific version of PAGE would still comply with the criterion of sufficient simplicity. The issue is taken up again further down in this thesis.

5.7 Conclusions on the realization of decision analysis in PAGE

In several aspects, PAGE2002 fulfils the criteria of decision analysis well. It is a comparatively simple model explained in clearly arranged publications and written for software that is easy to use. Especially when PAGE was chosen as a basis for the calculations in the Stern Review, an intensive peer review of the model took place and was welcomed by the modeller. The probabilistic approach with Monte Carlo analysis openly displays the uncertainty in ranges of inputs and results. This probabilistic approach is an important contribution to openly flagging uncertainty inherent in any cost model of climate change. This is a very valuable advantage of the PAGE model compared to other approaches. The theory of decision analysis directly suggests these valuable features, and therefore it can be concluded that the PAGE model benefits from the theoretical foundation chosen.

But there are also drawbacks to the application of decision analysis in PAGE and the consequent claim that PAGE allows decision makers to use the model as an aide to structure their ideas and thus reach a coherent decision based on their own values. Even though PAGE is a comparatively simple model, the issue of climate change costs is so complex that it is necessarily difficult for problem owners to judge their own accordance with the model assumptions. For ethical parameters like the pure rate of time preference, it is helpful that they can be easily changed by model users, and different values have actually been used in the past. But a high level of expertise is necessary, to meaningfully change some other parameter values in PAGE. The most problematic features of PAGE are the impact sectors market and non-market damages. These are so highly aggregated and as a consequence so abstract that problem owners can hardly judge in how far the values are in accordance with their own opinions.

PAGE has been used by people from other scientific disciplines, but not from as big a range of different scientists and disciplines as would appear desirable from the point of view of decision analysis. Many of the scientists most deeply involved in cost-benefit analysis of climate change work on their own models rather than to modify others'. Lay people on the other hand usually do not have the capacity or possibility to change parameter values according to their personal beliefs. This lack of involvement from a wide range of people reduces the advantages of openly employing subjective probabilities.

Hypothesis 2 is therefore accepted. PAGE profits from the influence of decision analysis, but it does not fulfil all the criteria set out by the strand of decision analysis, which was chosen as the foundation of the model. Especially the representation of the impact sector is extremely aggregated and for this reason opaque. Nevertheless, PAGE is an important contribution to tackling the deficiencies that were identified in the traditional integrated assessment approach, namely hidden subjective valuations of the modeller in dealing with a highly uncertain topic.

Cost-benefit analysis of climate change as a public policy problem was clearly not the envisaged area of application of decision analysis. But the basic idea behind embarking on this new approach is reasonable. Therefore, it is not necessary at this point to reject the endeavour of producing a cost-benefit model of climate change that is in line with the basic ideas of decision analysis, even if some amendments for the unusual area of application need to be made. There may be scope for further improvement.

The impact sector was identified as the most problematic feature of PAGE from the perspective of decision analysis. In the following, a specific representation of the impacts from the agricultural sector is exemplarily developed. The evaluation of this attempt shall contribute to the appraisal of the possibility and desirability of specific impact sectors in PAGE – and whether this is an option to significantly improve the coherence of the model with the principles of decision analysis. As the basic goal of sufficient simplicity in PAGE shall be maintained in spite of a more complex representation of the impact sectors, simplicity in the agricultural impact sector is a noteworthy, but also non-trivial goal. The development of the impact sector representation is a tightrope walk between aspiring after simplicity and offering enough detail to move away from the abstract level where problem owners can hardly form a subjective opinion on the accuracy of the chosen numbers. Hypothesis 3 is accordingly formulated as follows:

Hypothesis 3:
An impact representation split into single sectors and founded in up to date scientific impact research as presented in the IPCC Reports helps to overcome the major shortcoming of PAGE with respect to decision analysis. Sectoral impact figures facilitate the decision makers' judgement whether they agree with the impact assumptions in the model.

Part III

Proposal for the representation of the agricultural sector in PAGE

Climate change impacts in the agricultural sector affect two of the parameters hitherto used in PAGE: market and non-market impacts. Losses or gains in agricultural production have a market value, but they also have consequences for the number of people at risk of hunger. Hunger, or the avoidance of hunger, has no market value. But it is obviously a consequence of climate change that severely reduces the welfare of the people affected. Therefore any impact valuation of the agricultural sector that ignores the increase or decrease of people at risk of hunger is a seriously incomplete treatment of the problem. In the following, these two aspects are assessed separately.

6

Market impacts of climate change in the agricultural sector

As for other parameters in PAGE, the IPCC is deemed to be the source with the highest authority for the issue at hand. The problem which was mentioned for the aggregated impact numbers cited in the Third Assessment Report is only less severe, not resolved completely for the numbers on the agricultural sector. The IPCC report relies on results from underlying studies, and the assumptions of these studies are not all apparent to the reader. But, compared to calculations of the overall costs of climate change, estimates for example on expected changes in agricultural production are less severely influenced by subjective choices of the modeller, especially as ethical choices such as the discount rate or the valuation of the risk of human death play a minor role. The uncertainties attached to yield estimates are considerable – but they are more discernible than those of the highly aggregated cost estimates. And considering the extremely thorough development of the IPCC reports, they are the best that can be done to gather peer-reviewed estimates reflecting not just the appraisal of a few single scientists.

The most recent relevant publications from the IPCC are the Fourth Assessment Report from 2007 and the IPCC Technical Paper on Climate Change and Water. More results on the costs of yield losses caused by climate change are prepared by the Postdam Institute for Climate Impact Research (PIK) (Lotze-Campen 2009). The PIK model is an optimization model that answers the question: how can a certain given mix of crops be grown optimally and at what cost? These costs may be compared for a world without climate change and a world with climate change. The model was not constructed to predict the loss of yield, but rather the costs of maintaining a given yield quantity despite climate change. The impact of climate change is thus directly given in dollars, a very convenient unit for cost-benefit analysis. But a few drawbacks to this approach exist as well: for example some farmers simply don't act as in the optimization model (Löfgren and Sherman 1999: 663), a fact that is not captured by the approach. Second, beyond a certain level of climate change it is questionable to which level production growth can be driven through simple increase of financial input, an assumption underlying the PIK-model. Furthermore the modelling of yield losses due to floods is less advanced than the modelling of the effects of drought. The third cause of yield losses, sea-level rise, equally awaits an adequate treatment. (Lotze-Campen 2009)

6.1 Approach for quantifying market impacts in the agricultural sector

6.1.1 Data source

In the IPCC Fourth Assessment Report, results from many different studies on productivity changes for maize, wheat and rice are presented in a graphical format (Easterling et al. 2007: 286 – see figure 6.1). This cross-study compilation of results is here chosen as the main basis for productivity change estimates and thus market impacts in the agricultural sector of cost-benefit analysis of climate change.

In the graph, figures are given for temperature changes between 1°C and 5°C, not just for a CO_2-doubling as was the case in most studies cited in Part 1. This is an important property of the numbers, as the aim of cost-benefit analysis of climate change is to identify the overall cheapest level of global warming, taking together the costs for mitigation, adaptation and residual damages – or at least the optimal speed of mitigation action in the near term with the option to readjust the policies later. Therefore the mitigation costs and the costs for adaptation and residual damages need to be compared for different levels of global warming. A comparison for just one level of warming delivers a very limited type of information, that may not even help with the decision how to tackle mitigation in the near term. If, for example, a cost-benefit comparison were to yield the result that it is more expensive to prevent a 2°C warming than to bear the costs of adaptation and residual damages, this would not indicate that little mitigation is necessary today. Even to prevent a 2.5°C or 3°C warming, mitigation action needs to be very decisive in the near term (cf. Fisher et al. 2007: 198). Equally, when limiting global warming to 2°C is assessed to be better than accepting all the damages for this level of warming, nothing is as yet known about the profitability of limiting global warming to less than 2°C in the long run.

To deal with this issue, most integrated assessment models of climate change (e.g. FUND, DICE, PAGE) calibrate the impacts for a certain temperature, for example 2.5°C, from the literature. They then assume an exponential or potential function to extrapolate to other temperature levels. Little is known about the functional form of this impact-temperature relationship, especially when it is aggregated over various impact sectors (cf. section 2.12). For single sectors, some considerations as to the general shape of impact functions are given in Hitz and Smith (2004: table 1), but function parameters remain highly uncertain and even the general form is uncertain or unknown for many sectors.

PAGE employs a triangular probability distribution function instead of a point estimate for the impact function exponent to accommodate this uncertainty. The formula extending impacts to higher temperatures is

$$\text{Impact(temp)} = (\text{impact at } 2.5°\text{C warming}) \cdot (\text{temp}/2.5)^{x} \qquad (6.1)$$

x being the impact function exponent. Upper and lower bounds are 1 and 3, with a most likely value of 1.3 for the impact function exponent. DICE and FUND use different impact function exponents for different impact sectors. For agricultural damages FUND and DICE employ functions with a linear and a quadratic element (Nordhaus and Boyer 2000: 92; Nordhaus 2007b: 142; Tol 2006: 4).

By doing this, the models extrapolate beyond existing studies, because only a sparse set of estimates existed when the models were developed (Nordhaus and Boyer 2000: 89). In the Fourth Assessment report, yield change results from 69 studies were published that cover different levels of global warming between 1°C and 5°C. The results are displayed in figure 6.1. It is now the best option to use this available knowledge for the function of impacts at different degrees of global warming.

6.1.2 Applying the data to PAGE regions

To make the information from 6.1 useful for PAGE, it needs to be applied to the eight regions that exist in PAGE. It is assumed that the results for mid- to high-latitude apply to the regions European Union before the accession of the 12 new member states (EU15), Former Soviet Union and Eastern Europe (FSU & EEU), and USA. Further it is assumed that the results for low latitude apply to China and Centrally Planned Asia (China & CPA), India and South East Asia (India & SEA), Africa and the Middle East (AFR & ME), and Latin America (LA). For Other OECD (Oth. OECD) it is assumed that the average of the two regional specifications in the IPCC graph is the best approximation of the situation.

To obtain data on the size of the gross agricultural product (GAP) of the regions, figures on the overall GDP of the regions is taken from the PAGE model and multiplied by the GAP/GDP relationship. Information on these relationships

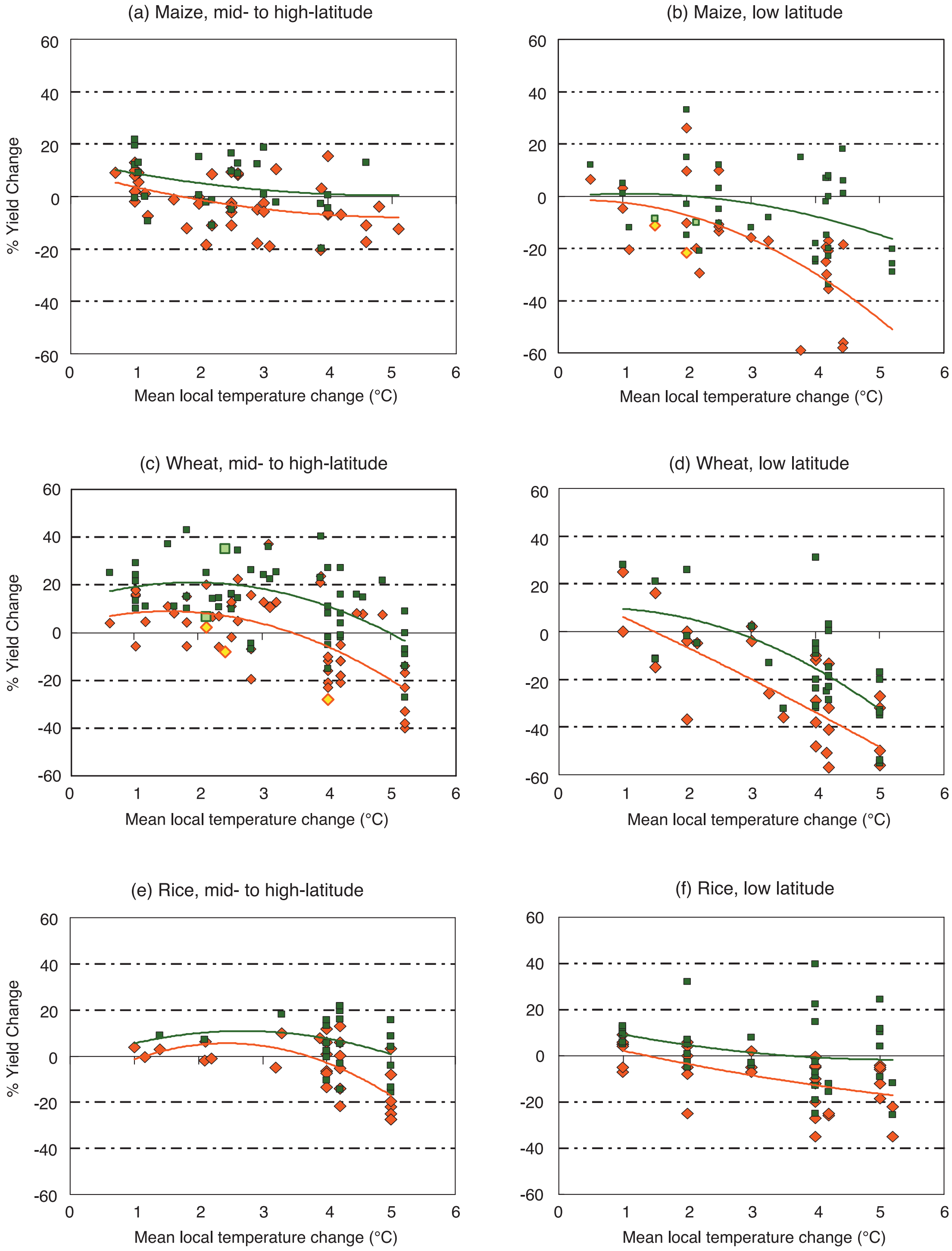

Figure 6.1: Productivity changes caused by global warming from 69 published studies at multiple simulation sites without adaptation (red) and with adaptation (green). (Easterling et al. 2007: 286)

was gathered from World Bank data (2007 data from World Bank (2009b)). As data was not available tailored to the PAGE regions, numbers from the most important countries in every region were used: For the combination of countries using the Euro as their currency the GAP is 2% of GDP. This is taken as an adequate approximation for the region EU15. In Russia, GAP amounts to 5% of GDP, for the whole of Europe and Central Asia the fraction is given as 7%. As it is only 2% for the Euro-countries, it must be considerably higher than 7% in Central Asia. 8% is taken as a number for FSU & EEU. In the USA GAP is 1% of GDP, for China & CPA the figure for China is used (12%); and for the PAGE region India & SEA, the World Bank figure for South Asia is employed (18%). For Africa & ME the average of the figures for "Middle East and North Africa" and "Sub Saharan Africa" is a suitable number (13%), as the GDP in both of these regions was almost equal in 2007. World Bank data are available for Latin America and the Caribbean (5%) and were subsequently used. For Other OECD the World Bank data from high income OECD of 2% is taken. Table 6.1 summarizes the numbers used.

The regional figures for the relationship between agricultural production and GDP that were used for the calculation of productivity changes above add up to a weighted global average proportion of GAP of 5.9% of gross world product. According to the most recent World Bank data, the world agricultural production is 3% of the gross world economic product (World Bank 2009a). Two reasons can be given for this difference: First, the latest available regional data was partly from earlier dates, and the proportion of agriculture in the overall GDP has been declining, a trend which may be slowed or stopped by rising prices for agricultural commodities in the future. Second, not for all PAGE regions data was available, so sometimes a figure was deduced from data for a different regional break-up. During this process errors may have been introduced.

EU	2 %
FSU & E.Eur	8 %
USA	1 %
China & CP Asia	12 %
India & SE Asia	18 %
Africa & ME	13 %
Latin America	5 %
Other OECD	2 %

Table 6.1: Contribution of gross agricultural product to GDP in the eight PAGE regions

It has been tested whether these errors are likely to have distorted the overall result. This is not the case. During the calculation, not only older data for the proportion of agriculture, but also earlier data for the regional GDPs have been used. This was done, because the earlier data was available exactly for the PAGE regions and it is the data used in PAGE2002. It is helpful to derive potential impact figures for the model from the same data basis. This is no major concern in the

PAGE region	**Data used from**	**Maize**	**Wheat**	**Rice**
		million metric tons		
EU15	FAOSTAT 2009 (North, West and South Europe)	47.250	109.550	2.675
FSU & E.Eur	Cline 2007 (Russia) and FAOSTAT 2009 (Eastern Europe)	36.950	137.375	1.225
USA	Cline 2007 (USA)	256.800	55.000	9.700
China & CP Asia	Cline 2007 (China, Vietnam and Myanmar)	124.000	90.800	231.500
India & SE Asia	Cline 2007 (India, Indonesia, Bangladesh, Pakistan, Thailand, Philippines)	34.500	90.100	264.700
Africa & ME	FAOSTAT 2009 (Africa)	49.575	21.925	21.175
Latin America	FAOSTAT 2009 (Latin America)	70.050	21.700	23.150
Other OECD	Cline 2007 (Canada, Australia, Mexico, Japan)	29.600	43.100	12.000
Sum of the above:		648.725	569.550	566.125
World – FAOSTAT 2009:		732.175	616.075	633.850
Percentage of world yield covered by the countries/regions above:		88.6 %	92.4 %	89.3 %

Table 6.2: Data sources for yield quantities of maize, wheat and rice in the PAGE regions

context of applying the IPCC yield change data to the PAGE regions, because the GDP figures are here used to define the relative importance of different PAGE regions' GDPs, not as absolute numbers. The absolute global GAP figures derived with this method are 4.8% of GDP compared to recent World Bank Data on gross world product (US$ 54.6 trillion). This is still higher than the 3% given as the latest share, but close enough to historical data to exclude major distortions of the overall result. Furthermore, productivity losses affect not only the agricultural sector itself, but also the industry for the processing of agricultural goods. Therefore slightly higher numbers than only the proportion of GAP with respect to GDP may be warranted here.

Where impacts are given as a percentage of GDP, the figure of 54.6 trillion is used as a basis for the calculation. This implies that 4.8% of the economy are directly affected through climate change impacts in the agricultural sector. If figures are to be used directly in PAGE2002 and therefore adapted to the GDP assumptions there, they need to be converted to a global GDP of 43.8 trillion.

Data about the proportion of wheat, maize and rice are four year averages from FAO (FAO (2008a) years 2004–2007 and cited from Cline (2007: 90) years 2001–2004). Data was not always available for the PAGE regions; therefore the following data as displayed in table 6.2 was used.

For the further calculations only the proportion of the three cereal types in each region is important. Therefore it is considered sufficient, that the countries used as a data basis here cover between 89% and 92% of world production for the respective

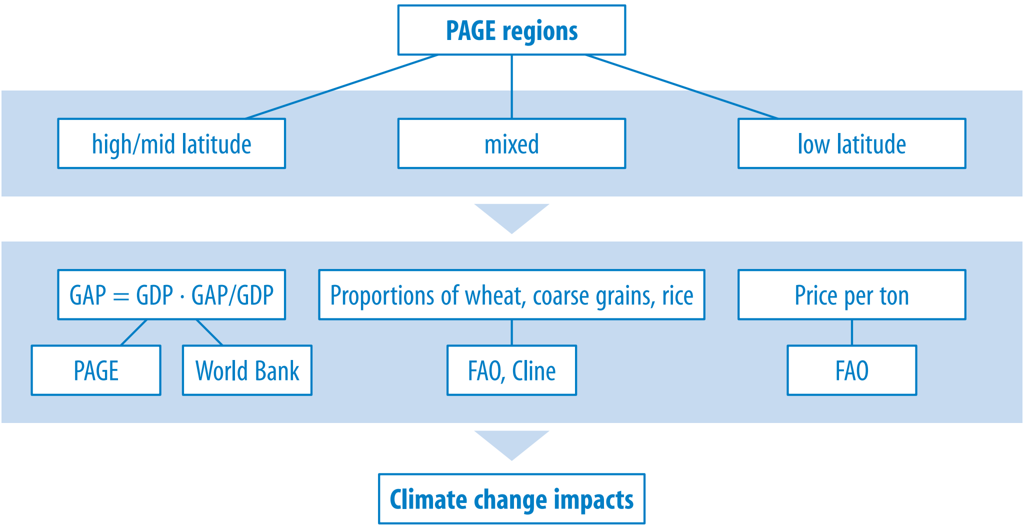

Figure 6.2: Sources for the necessary data to apply productivity change results from the IPCC's Fourth Assessment Report to the PAGE regions and structure of the calculation

cereals. In a field with high uncertainties like the impacts of climate change on agriculture, more precision in this point could hardly improve the quality of the overall results. Furthermore, neighbouring countries often grow similar cereals.

Prices per ton of product are also from FAO statistics. The numbers used are 95$/t for maize, 127$/t for wheat and 170$/t for rice. 2009 prices are actually higher. Depending on the exact type of cereal they were around 170$/ton for maize, 215 $/t for wheat and 450 $/t for rice (FAO 2009a). But the relationship of the prices is similar, and only this relationship influences the outcome of the calculation where the prices are used. Figure 6.2 illustrates the overall compilation of data:

6.1.3 Evaluation of yield productivity changes reported by the IPCC

The yield productivity changes are evaluated from the IPCC graphs (figure 6.1) for four different levels of global warming: 1°C, 2.5°C, 4°C and 5°C. The metric indicated in the graph is yield change in percent, but the figures can be treated as yield productivity changes in the context of this thesis: Looking at the global impacts of climate change, yield changes describe the change in overall yield after taking into account possible changes in the area under production. The term 'yield productivity changes' is used to indicate how much the yields change on a given area due to global warming. In the adaptation options considered in the IPCC graph (figure 6.1), a change in the area under production was not considered.

Different studies have led to notably different yield productivity change results for the same temperature rise, even when taking into consideration whether they include adaptation or not. To account for these uncertainties, the probabilistic approach of PAGE is used here as well. Triangular probability distribution functions are developed to account for the spread of results from different studies. The lower and upper bounds of the triangular probability distribution functions are taken to be the lowest and the highest yield estimates for the corresponding temperature. This is probably an underestimate of true uncertainty, as it is unlikely that all possible outcomes have been captured in the results of the studies. The spread of results in the IPCC graphs indicates the spread of opinions about the most likely result rather than an illustration of all possible outcomes. This should be kept in mind for the interpretation of results.

The scope of adaptation under real-world conditions is still very uncertain (see chapter 2.6). Therefore both estimates with and without adaptation are used. For the best guess, that is the mode in the probability distribution function, the value of the average line for studies with adaptation is used as a basis.

However, these numbers are not yet the best guess possible. The IPCC draws attention to the fact that not all relevant factors were adequately taken into consideration in the yield change studies. In the IPCC Technical Paper on Climate Change and Water the authors write:

> It is expected that projected changes in the frequency and severity of extreme climate events, such as increased frequency of heat stress, droughts and flooding, will have significant consequences on food, forestry (and the risk of forest fires) and other agro-ecosystem production, over and above the impacts of changes in mean variables alone. In particular, more than 90% of simulations predict increased droughts in the sub-tropics by the end of the 21st century, while increased extremes in precipitation are projected in the major agricultural production areas of southern and eastern Asia, eastern Australia and northern Europe. It should be noted that climate change impact models for food, forest products and fibre do not yet include these recent findings on the projected patterns of precipitation change; negative impacts are projected to be worse than currently computed, once the effects of extremes on productivity are included. (Bates et al. 2008: 61)

Thus, the IPCC states that the negative yield impacts will probably be worse than computed in the current models. It is here considered unsatisfactory to ignore the point altogether. But it is impossible to say how much worse the negative impacts will be. Any inclusion in an agricultural impact module for PAGE necessarily conveys a high degree of subjectivity, as no scientific numbers on the size of the effect exist. As explained above, in PAGE the existence of subjectivity is openly admitted, clearly flagged and accommodated via probability distribution functions. Ignoring the effect of extreme weather events although qualitative but no quantitative knowledge is available in the IPCC report is here deemed to be the worse alternative compared to a rough inclusion, albeit with subjective probabilities. Anyway, ignoring the effect would also be a very subjective decision.

In the following an attempt is made, to account for the possible negative effect of extreme events in a conservative fashion. Conservative here is meant to imply that the negative consequences of extreme climate events are rather underestimated than overestimated, that is yield is rather overestimated. Like this, the function should be better than an alternative function ignoring the effect altogether.

What is known about the possible magnitude of the consequences of extreme climate events in contrast to average temperature and precipitation changes? The IPCC notes on this issue:

> Projected changes in the frequency and severity of extreme climate events will have more serious consequences for food and forestry production, and food insecurity, than will changes in projected means of temperature and precipitation (high confidence). (Easterling et al. 2007: 299)

This quotation suggests, that the negative yield impacts may be more than twice as big as reported in the models. However, this would lead to a significant likelihood of some regions losing all their harvest of wheat at a 5°C warming. This is not in line with the general descriptions of the situation in the chapter on food, fibre and forests in the IPCC Fourth Assessment Report (Easterling et al. 2007). Furthermore, other adaptation options than those regarded in the studies might be available. Therefore, to remain on the conservative side as explained above, the negative values of the triangular probability distribution functions are multiplied by 4/3, that is their absolute value is increased by one third. To simplify the calculation, only the upper bound, most likely value and lower bound of the probability distribution functions are tested and, given negativity, multiplied by 4/3.

The positive yield change values are not corrected for the effect of extreme climate events. The upper end of the probability function is non-negative for all yield change probability distribution functions, except wheat in low latitudes at a

5°C warming. They remain unchanged and therefore the results without correction for the effect of extreme events remain represented in the probability distribution functions.

To estimate productivity losses for the entire agricultural sector in each region, it is necessary to ascertain the importance of the three cereals in the PAGE regions. This importance could either be measured by quantity in weight, or by the contribution to gross agricultural product thus including prices as another weight factor. As the aim of this section is to estimate market impacts, the importance of the three cereal types is in the following measured by the contribution to the region's gross agricultural product. For this purpose, the regional yield of each of the three cereals is multiplied by the price on world markets, and then further multiplied by the impact probability distribution function for the cereal type in question. The sum of the results for rice, maize and wheat is then multiplied by a scaling factor. The scaling factor expresses which part of the region's GAP is produced by the quantities of wheat, rice and maize that were used as a data basis for the proportion of the three cereal types in every region. The scaling factor of course shows a much smaller proportion of GAP covered by the data than the 89–92% mentioned above. Not only are about 10% of the global cereal yield missing from the data basis above, but all other contributions to GAP like fruit, vegetables, meat and fish are not covered by the data. Rice, maize and wheat are not the only important agricultural products. Yet, as productivity changes from a significant number of studies are only reported for these crops in Easterling et al. (2007), they are taken here as an approximation for the effects of climate change on the whole agricultural sector. Easterling et al. show that climate change will very likely affect the other agricultural products as well. Examples are given among others for meat and fish. When more data is available on the likely numerical impacts of climate change, it is advisable to integrate this knowledge into the agricultural impact sector of PAGE. Meanwhile, the best guess is that other agricultural sectors are affected similarly to the cereal production covered above.

The formula for the calculation is:

$$I_{prod} = \left(Q_{wheat} \cdot P_{wheat} \cdot pdf_{wheat} + Q_{maize} \cdot P_{maize} \cdot pdf_{maize} + Q_{rice} \cdot P_{rice} \cdot pdf_{rice}\right) \cdot Sc \quad (6.2)$$

where I_{prod} is Impact of climate change on productivity, Q is the quantity produced, P the world market price, pdf the probability distribution function describing the yield losses and Sc the scaling factor describing the relationship between the market value of the cereal yield covered in the data basis and the overall GAP of the region.

6.1.4 From local to global temperature change

The productivity changes in the IPCC graphs (figure 6.1) are the basis for the calculations described above. In the IPCC graphs, productivity changes are given as a function of local temperature rise. But PAGE uses the average global temperature increase as the measure for global warming. Therefore the temperature change figures from the graph need to be adapted to fit the numbers in PAGE. Two effects contribute to the difference between local temperatures and global temperatures: Global warming is expected to occur faster in high latitudes than in low latitudes, and it is expected to be stronger over land than over sea (Sutton et al. 2007). Therefore, to obtain impact estimates for global warming levels of 1°C, 2.5°C, 4°C and 5°C, different local temperature changes need to be used for the calculation.

The land-sea ratio of global warming differs with the geographical latitude. It is assumed that in low latitudes warming over land is 1.25 times stronger than on average over land and sea; the value for mid- and high latitudes is assumed to be 1.3 (Sutton et al. 2007). Therefore the four levels of global temperature change chosen above (1°C, 2.5°C, 4°C, 5°C) are multiplied by these values to obtain land only temperatures for the respective latitudes.

Fischer et al. (2005: figure 2, p. 2072) have published separate relationships of temperature rise to CO_2-concentration for developing and developed countries. The difference in temperature rise in the two world regions increases for higher levels of global warming. This information is used to approximate the difference between low latitude and mid/high latitude in figure 6.1. The following values for the difference in global warming is used: 0.2°C difference for 1°C warming, 0.4°C difference for 2.5°C warming, 0.6°C difference for 3.6°C warming and 0.8°C for 4.4 °C warming. Table 6.3 displays the local temperature change values that correspond to the global values. Numbers for both mid/high and low latitude are higher than the global temperature, because they apply only to the areas over land, not over sea.

Unfortunately, the productivity changes for the global warming levels 4°C and 5°C cannot be taken from figure 6.1, as the highest indicated local temperature change is 5°C, which corresponds to lower global values. 3.6°C is the highest temperature, for which direct results from the mid/high latitude are available. For

Global temperature	Local temperature mid/high latitude	Local temperature low latitude
1.0 °C	1.4 °C	1.2 °C
2.5 °C	3.5 °C	2.9 °C
3.6 °C	5.0 °C	4.2 °C
4.4 °C	6.1 °C	5.1 °C
5.0 °C	7.0 °C	5.8 °C

Table 6.3: Corresponding levels of global warming at global level, for mid/high latitudes and for low latitudes; own calculations based on Sutton et al. (2007) and Fischer et al. (2005)

the low latitude, productivity change estimates reach up to a global warming of 4.4°C.

To use data from the IPCC graphs for as large a temperature range as possible, the values for 3.6° / 4.4° temperature change are derived from the graphs and global values for 4°C and 5°C are estimated with mathematical inter- and extrapolation. A 4°C warming in low latitude regions would theoretically be within the range of the IPCC graphs, but no direct study results are available for the corresponding local warming in the graphs. Therefore no data knowledge is lost when mathematical interpolation is used. For 4.4°C warming numbers are directly available only for low latitudes. For high latitudes, the productivity changes are estimated from figure 6.1 with a continuation of the trend. The trend for maize is very stable towards the end of the graph. This means, that for maize the same figures are taken as for the 3.6°C warming. Rice is mainly produced in regions that are counted to the low latitudes in this calculation; therefore the figures for high latitudes have no significant influence on the overall final result.

The biggest subjective influence enters the calculations for the high temperature estimate for wheat in high/mid latitudes. But an estimate of mid/high latitude yield changes for 4.4°C warming is necessary in order to use the available data for this level of temperature change from developing countries in a global aggregate. It would be a loss of valuable information not to use the data available for 4.4°C temperature rise in low latitudes and rely on purely mathematical extrapolation for all warming levels above 3.6°C. Therefore the uncertainty of the wheat estimates is accepted so as not to lose the other more reliable information available.

As a default option for wheat in mid and high latitudes, the inter- and extrapolation to 4°C and 5°C is effectuated linearly. Another possibility is discussed further down in connection with the result graphs. Thus, the consequences of the different options can be captured graphically and users can more easily decide which version seems most likely to them.

Another possible difference between the warming specifications in figure 6.1 and those in PAGE is the base year. In PAGE, pre-industrial CO_2-concentrations and temperatures are the basis for all calculations. In the explanations of the IPCC graphs (figure 6.1 here) in the original source (Easterling et al. 2007: 285f), the base year is not named. However, several indications point to the base period being pre-industrial times just as in PAGE. First, temperature increases ranging from 1 to 2°C are called typical for the next decades (Easterling et al. 2007: 285). This suggests that the base year is in the past and a notable warming has already taken place, soon approaching the lower value mentioned above: 1°C. Second, pre-industrial values are frequently mentioned as a point of reference in other places of the IPCC Fourth Assessment Report, e.g. in IPCC (2007b: figures SPM 6 and SPM 11). Among these are the presentation of the post-SRES scenarios, which are also displayed with warming figures compared to pre-industrial temperature levels. Therefore, no further adaptation for the base year is effectuated here.

Striving for accuracy as with the conversion of global to local temperatures can be in conflict with the aim of simplicity, which was stated above. Giving up simplicity is even more dubious, when the increase in accuracy comes at the price of using even more uncertain parameters. To a certain extend this is the case above. It is certainly more accurate to separate local and global levels of temperature increase and failing to do so may distort results rather considerably. On the other hand, the parameters used for the conversion are uncertain, and even more so when applied to just two broad and crude geographical regions. Therefore, the results with and without the conversion of global to local levels of temperature increase were compared to make an appraisal of the necessity of this calculation possible. The results showed a very significant difference, and the conversion to global temperatures is therefore effectuated in the following.

Another factor that has not been regarded here are the adaptation costs. Adaptation measures have been integrated in part of the productivity change estimates in figure 6.1. The most likely value for the probability distribution functions derived from these data is based entirely on results that assume adaptation to take place. Not all of these adaptation measures come at zero costs, and therefore the adaptation costs should be counted as costs of climate change together with the costs of the residual damages. For adaptation measures in 2050, a cost estimate exists (Nelson et al. 2009: 16). The authors find that the additional annual investments

Warming	5% percentile	Mean	95% percentile
1.0 °C	2.3 %	6.1 %	9.6 %
2.5 °C	−12.7 %	−5.4 %	1.5 %
3.6 °C	−22.9 %	−14.5 %	−6.4 %
4.4 °C	−32.0 %	−23.4 %	−15.4 %

Table 6.4: Global productivity changes, mean and 90%-confidence interval; data sources given in the text

needed to return the child malnutrition numbers to the no climate-change results are over 7 billion US$. However, no applicable estimates of the adaptation costs are available for all relevant levels of global warming, or for a wide range of adaptation strategies (cf. Adger et al. 2007: 719). They are not integrated into the following calculations.

6.2 Productivity change results

Table 6.4 and figure 6.3 (a) display the mean productivity changes to be expected as well as the 90%-confidence interval for the four levels of temperature rise for which direct impact data were available. It should be kept in mind that the confidence interval is an underestimate of true uncertainty as only yield change assumptions were considered that had been the best-guess result of one of the 67 studies in the survey.

Figure 6.3 (b) shows the same data, but with additional points for 4°C and 5°C warming to illustrate the consequences of linear inter- and extrapolation. The 5°C results for the mean and lower bound were extrapolated from the data points for 3.6°C and 4.4°C. The 5°C result for the upper bound was derived via extrapolation from the data points for 2.5°C and 4.4°C. This gives a slightly wider confidence interval. The extrapolation from just two data points is subject to uncertainties due to the stochastic properties of such a small sample. Therefore the wider confidence interval is considered appropriate. Table 6.5 shows mean results for the individual PAGE regions.

The mean productivity changes that are to be expected according to the calculation procedures above are a gain of 6% for a 1°C warming, a 5% loss for a 2.5°C warming and a loss of 30% for a 5°C warming. But the range of possible yield changes is wide. The 90% confidence interval encompasses yield changes of +2% to +10% for a 1°C warming, −13% to +2% for a 2.5°C warming and −39% to −21% for a 5°C warming.

Region	1°C warming	2.5°C warming	3.6°C warming	4.4°C warming
EU	12.6 %	4.9 %	−12.1 %	−21.4 %
FSU & E.Eur	13.5 %	5.6 %	−12.9 %	−23.1 %
USA	6.6 %	0.2 %	−7.5 %	−10.5 %
China & CP Asia	4.5 %	−7.6 %	−14.1 %	−22.4 %
India & SE Asia	5.1 %	−6.5 %	−11.9 %	−19.3 %
Africa & ME	4.1 %	−9.9 %	−20.3 %	−31.5 %
Latin America	3.4 %	−10.3 %	−20.4 %	−31.5 %
Other OECD	8.8 %	−2.9 %	−17.9 %	−29.2 %
Global Average	6.1 %	−5.4 %	−14.5 %	−23.4 %

Table 6.5: Mean productivity changes due to climate change in the eight PAGE regions; data sources given in the text

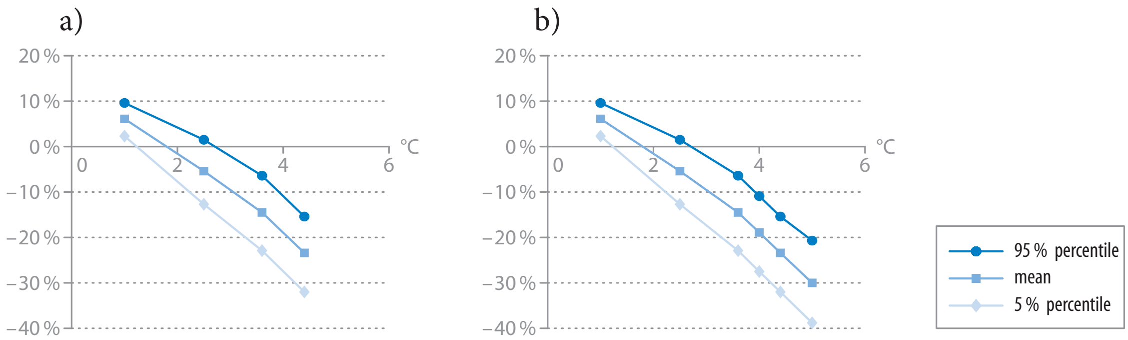

Figure 6.3: Projection of changes in gross agricultural product (mean and 90%-confidence interval) as a function of global warming (°C) a) for the four levels of temperature rise for which direct impact data were available; and b) with linear inter- and extrapolation to 4°C and 5°C; own calculations based on the sources given in the text

The linear interpolation to 4°C is not problematic. The curve is not strongly bent in that part and the two calibration points are sufficiently close together. Compared to other uncertainties, the possible error of this interpolation is small. The results are summarized in table 6.6.

The extrapolation to 5°C is more speculative, as no data points are available to calibrate the slope of the further curve. As further information that can be used to judge the adequacy of different extrapolation formulae, figure 6.1 can once more be consulted. Approximating curves for productivity changes with and without adaptation as a function of temperature rise are plotted in the graphs. The behaviour of these approximating curves towards the upper end of the temperature

Warming	5% percentile	Mean	95% percentile
1.0 °C	2.3 %	6.1 %	9.6 %
2.5 °C	−12.7 %	−5.4 %	1.5 %
3.6 °C	−22.9 %	−14.5 %	−6.4 %
4.0 °C	−27.5 %	−18.9 %	−10.9 %
4.4 °C	−32.0 %	−23.4 %	−15.4 %
5.0 °C	−38.8 %	−30.0 %	−20.7 %

Table 6.6: Productivity changes caused by climate change – global average based on global temperature rise and linear extrapolation (positive numbers are gains)

scale can be used as an indication of how the result curve above can be expected to continue to 5°C.

In figure 6.1, the approximating curves in two of the six graphs tend to bend downwards less for higher levels of temperature rise than for medium levels (the second derivation of the curve is positive): maize in mid- to high latitude and rice in low latitude. But this characteristic is not very pronounced. For the other four graphs, the opposite is true: the downward slope of the curve increases for higher levels of temperature rise, in some cases very distinctively so. All together, figure 6.1 delivers a hint, that the productivity tends to decrease faster at higher levels of temperature change. From this it can be deduced, that the linear extrapolation employed above is not the optimal choice.

In the following, a different method is used for the 5% percentile that takes into account the possibility that the curve bends down faster at higher temperatures. The intervals between the three preceding calibration points 2.5°C, 3.6°C, and 4.4°C are not widely different. It is assumed, that the increase in the average slope from the interval between 3.6°C and 4.4°C compared to the preceding interval is maintained for the average slope of the following, extrapolated part of the curve: SlopeC = (SlopeB − SlopeA) + SlopeB. For example, the average slope between 2.5°C and 3.6°C warming is −217. The average slope between 3.6°C and 4.4°C is −288. It is then assumed, that the average slope between 4.4°C and 5.0°C is −359. This method is only employed for the lower bound of the 90% confidence interval. For the mean the linear extrapolation is maintained and for the upper bound the linear extrapolation with 2.5°C as a calibration point, leading to a comparatively flat slope remains unchanged from above. Figure 6.4 illustrates the result of this extrapolation compared to the graph with only those four values that were directly derived from the data in the IPCC Fourth Assessment Report.

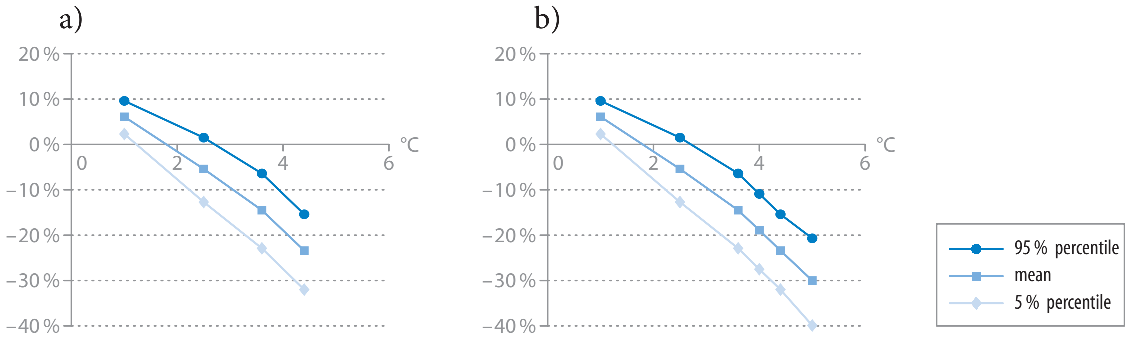

Figure 6.4: Productivity change projections (mean and 90%-confidence interval) as a function of global warming (°C) a) for the four levels of temperature rise for which direct impact data were available; and b) with inter- and extrapolation to 4°C and 5°C; own calculations based on the sources given in the text

Warming	5% percentile	Mean	95% percentile
1.0 °C	6.1 %	2.3 %	9.6 %
2.5 °C	−5.4 %	−12.7 %	1.5 %
3.6 °C	−14.5 %	−22.9 %	−6.4 %
4.0 °C	−18.9 %	−27.5 %	−10.9 %
4.4 °C	−23.4 %	−32.0 %	−15.4 %
5.0 °C	−30.0 %	−39.9 %	−20.7 %

Table 6.7: Productivity changes caused by climate change – global average based on global temperature rise and non-linear extrapolation (positive numbers are gains)

The curves in figure 6.4 take into account a range of possible developments of climate change impacts at higher temperatures. A slightly decreasing slope (95% percentile) is represented as well as a stable slope (mean) and an increasing slope (5% percentile). This is a rather conservative estimate considering the evidence from the IPCC Fourth Assessment Report. The data there suggest a faster decline in grain productivity for higher levels of global warming. The results are displayed in table 6.7.

In summary, the IPCC data indicates that global agriculture is likely to benefit on average from a small level of warming. But the effect becomes negative on average already for a warming of 2.5°C and is very clearly negative at 4°C and 5°C warming. For a 5°C temperature rise, with 95% probability the losses are bigger than 20% and most likely they are around 30%. There is even a 5% chance that the losses exceed 40%. A threshold temperature exists, beyond which the global productivity impacts turn from gains to losses. This threshold temperature is unknown, but probably below 2.5°C for global productivity. At the regional level, these threshold temperatures can vary considerably.

6.3 Welfare valuation of the yield losses – methodology

In the calculations above, productivity changes due to climate change were extrapolated to the PAGE regions on the basis of today's grain production structure. This is not yet a measure for welfare change, which would be the correct input to the cost-benefit analysis. Furthermore, the world's grain producers will not react to climate change by a production change exactly corresponding to the decrease in productivity. The demand for food is inelastic. A reduction in productivity leads to quickly rising prises. These rising prices in turn lead to increasing food production, compensating quantity-wise for part of the losses caused by decreased productivity. Figure 6.5 illustrates the relationship between the world with and without climate change:

The yield productivity decreases caused by climate change above a threshold temperature provoke a shift of the supply curve to the left. With the same inputs, a smaller quantity of grains can be grown. In the graph, a world with climate change and a world without climate change are compared for a given point in time, therefore changes over time independent of climate change are not reflected in the graph. For the time being, it is assumed that demand is not affected by climate change. This is true, as long as the world population is not notably reduced and the

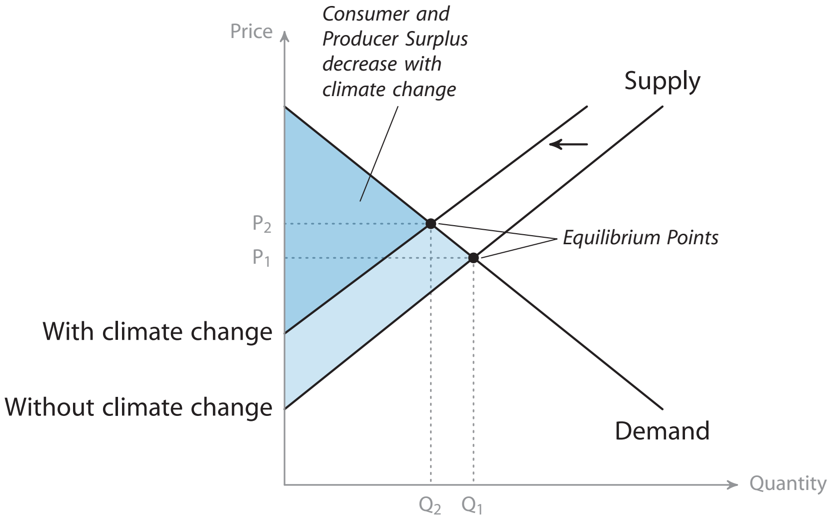

Figure 6.5: Consequences of reduced productivity on supply, demand, quantity, prices and consumer and producer surplus

ability to pay for nutritional standards is not significantly and over large parts of the population deteriorated through climate change. Either of these assumptions would be enough reason in itself to choose a very ambitious mitigation policy, regardless of the results from a cost-benefit comparison.

With climate change, a new equilibrium point is reached where supply and demand match. Prices are higher, the quantity produced is lower, and both consumer and producer surplus are smaller in the graph. The sum of consumer and producer surplus is usually taken to be the correct metric to measure welfare changes that are caused by the productivity losses (cf. Pearce et al. 1996: 186; Tsigas et al. 1997: 294).

There are several obstacles to correctly retrieving welfare changes based on this concept:

- The consumer and producer surplus can only be calculated, when the supply and demand curves are known.
- Global trade significantly affects the local supply and demand curves.
- The demand of a significant number of people does not materialize in the food markets, as the people do not have enough money to buy the food they need.

In the following these obstacles are assessed in more detail.

First, the consumer and producer surplus can only be calculated, when the supply and demand curves are known. In particular, the price elasticities of demand and supply need to be known at every point of the supply and demand curves left of the equilibrium point, that is for conditions that do not exist today. This data can therefore not be gathered empirically (cf. Cline 2007: 33; Mendelsohn 1998: 226). But even the price elasticities at the existing market equilibrium points are not easily quantified. They differ substantially among countries (Regmi et al. 2009). For a large number of countries like Brazil, Egypt, Indonesia and Russia the authors identified consumer price elasticities close to −0.4. For other countries like Iceland and Switzerland they found values around −0.2, for the US even −0.08. Price elasticities also vary according to the type of food. Income elasticities differ even more along income groups, and also according to the type of food considered (Regmi et al. 2001: tables B1 and B2).

Second, although global trade does not lead to globally uniform demand and supply elasticities, it significantly affects the local supply and demand curves (Darwin et al. 1995: 4). Some of the yield change estimates that were used as the basis for the triangular probability distribution functions include a range of adaptation measures. Among these are changes in planting, changes in cultivar, and shifts from rain-fed to irrigated agriculture (Easterling et al. 2007: 286). But they do not include the possibility, that production will partially move to different countries, that are less adversely affected by climate change. This further complicates the construction of realistic demand and supply curves.

In various studies, complex global general equilibrium models were used to assess the effects of climate change on agriculture (e.g. Reilly et al. 1994; Darwin et al. 1995; Tsigas et al. 1997; Parry et al. 1999; Fischer et al. 2001; Parry et al. 2004; Darwin 2004). It would be beyond the scope of the dissertation to develop a new global equilibrium model – but anyway, it is considered not to be in accordance with the principles of decision analysis to rely on any one such complex model for the evaluation of the impacts of climate change. Climate models are also very complex, but uncertainties come more predominantly from natural sciences. In global equilibrium models of the food markets, ethical assumptions are inherently embedded. For example, global equilibrium models capture demand only when it materializes in markets, the third point of criticism mentioned above. A detailed assessment of this aspect is presented further down. They further hinge on the assumption, that those regions experiencing production losses can buy the food they need on the markets. This presents difficulties as many of the biggest production losses are expected in very poor regions (Parry et al. 2004: 53; Easterling et al. 2007: 284).

In the following, results from major other studies and the conclusions from the IPCC are assessed for a compilation of the state of the art on welfare consequences of climate change impacts in the agricultural sector. In the IPCC Fourth Assessment Report, predictions on the development of cereal prices with rising global temperatures from five different studies are reported (Easterling et al. 2007: figure 5.3). Of these, Adams et al. (1995) focus on the US agriculture only. From the other four, the oldest study (Reilly et al. 1994) predicts prices below the baseline value without climate change for a warming of up to 4.5°C. The other three studies (Darwin 2004; Fischer et al. 2002; Parry et al. 2004) predict rising cereal prices compared to a world without climate change even at small temperature increases, the two latter studies at a faster rate than Darwin (2004). The results from Reilly et al. (1994) with a 10% price decrease at 4°C warming are not in accordance with the more recent conclusions by the IPCC in the Fourth Assessment Report (e.g. Easterling et al. 2007: 275). In the following, the three more recent studies are looked at in more detail.

In Darwin et al. (1995) results are given for changes in land classes that describe a few key parameters influencing yield prospects (table 13), for changes in total water runoff for eight world regions (table 16), changes in the value of existing cropland (table 15), changes in quantities and prices for agricultural commodities (table 19), and changes in GDP (table 28). Changes in consumer surplus are not reported. The accuracy of the study can be doubted on grounds of extremely optimistic adaptation assumptions (cf. Cline 2007: 11ff).

Fischer et al. (2001) report the impacts of climate change in four metrics: impact on world market prices (table 4.10), impact on GDP of agriculture (table 4.11), impact on cereal production (table 4.12) and impact on human cereal consumption (table 4.13). This is a considerable variety of information. Still, none of it replaces the consumer and producer surplus as a measure of welfare. Figure 6.6 illustrates the point. As the graphs are not based on real-world data they do not illustrate probabilities. In both parts of the graph random, but in the essential features possible curves for supply and demand are depicted to prove the possibility of the following phenomena.

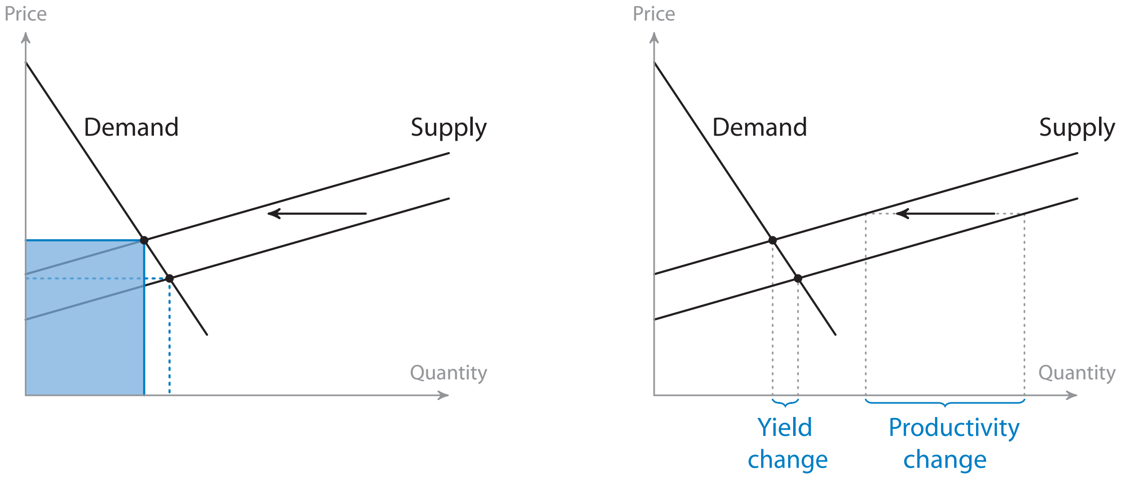

Figure 6.6: Significance of changes in gross agricultural product and in production quantity for the welfare assessment

First it is shown, that changes in the gross agricultural product are no sensible approximation for welfare changes. In the left graph, the gross agricultural product (GAP) without climate change is the area of the square between the origin and the corresponding equilibrium point marked by a dotted line. The GAP with climate change is the blue rectangle. Prices have risen and the quantity produced has decreased. As these two effects influence the GAP in different directions, the difference between the GAP with and without climate change is not necessarily large, as can be seen in the graph. The GAP with productivity reductions could theoretically even be bigger than the baseline GAP. Still, the loss of consumer and producer surplus is substantial.

Neither are the changes in production quantity a good proxy for welfare changes. In the right graph, the difference in production quantity with and without climate change is shown in the difference in quantity plotted on the x-axis. Again, the difference may be small, although the loss in consumer and producer surplus is considerable. This is the case, when food demand is highly inelastic, as it indeed is assumed to be. Pearce et al. concluded, that in the agricultural sector welfare losses are always bigger than yield losses, and more so for bigger yield losses (Pearce et al. 1996: 186; cf. European Commission 1999: chapter 13.10). At least the yield change always indicates the right direction of the welfare change, but it is still no satisfying proxy. For further illustration, the productivity change is depicted in the graph as well. The horizontal shift of a given point on the supply curve shows, how much the quantity that can be produced at the same price is reduced.

Therefore, although the results from Fischer et al. are very interesting and far-reaching, they are not in the right metric to serve as a sensible input to the agricultural impact module in PAGE. The same is true for the studies by Parry et al. Here results are given for food prices and production changes (Parry et al. 1999: S60, 2004: 57ff).

Tsigas et al. (1997) give both yield changes and welfare changes derived from the GTAP (Global Trade Analysis Project) general equilibrium model. It is therefore interesting to see, how these relate to each other. In the following, the model run without CO_2-fertilization is assessed, as these impact numbers are big enough to make the comparison meaningful. Some of the results for the model run with CO_2-fertilization do not diverge significantly from zero, and rounding errors are therefore more important.

The productivity changes they use as an input are between 16% and 26% (p. 284). From this, yield changes between 2 and 4.7% are derived by the equilibrium model, depending on the crop (p. 300). The welfare changes amount to 0–7.6% of gross domestic product (GDP) (p. 301), on average 1.7% (own calculations based on Tsigas et al. 1997: 301). In the general equilibrium model, the effects of yield productivity changes on all other sectors of the economy are assessed. It is therefore correct that Tsigas et al. give the welfare change as a percentage of overall GDP. It can be checked that they refer to global GDP, as their global GDP numbers are very similar to other GDP estimates from the literature for the 1990s. But in the graphs

Productivity change	Yield change	Welfare change as a share of GDP	Welfare change compared to the size of the agriculture sector
16 – 26 %	2.0 – 4.7 %	0.0 – 7.6 % (average 1.7 %)	~ 35 %

Table 6.8: Effects of climate change without CO_2-fertilization as given in GTAP (own calculations based on Tsigas et al. 1997)

above, only the gross agricultural product was in the focus of interest, not the whole GDP. Therefore, to empirically validate the statement that welfare losses in the agricultural sector can substantially exceed yield losses, it is necessary to compare the size of the welfare losses to the size of the GAP. In the early 1990s when the GTAP model was run, world GAP was about 5% of the world GDP (World Bank 2009b). For a rough comparison of the order of magnitude the welfare change of 1.7% is divided by 0.05. The welfare losses in all economic sectors amount to a sum that equals about 35% of GAP.[1] Therefore, the theoretical statements from above are validated empirically by the GTAP model: where demand is very inelastic as is the case for basic food, the yield changes will be substantially lower than the productivity changes, and the welfare changes are substantially bigger than the yield changes. Table 6.8 summarizes the results.

The results from Tsigas et al. are very interesting. However, they are not considered an adequate basis for the valuation of yield changes in PAGE. First, the results of one model can hardly be called a scientific consensus or at least a strong scientific basis. But this would be necessary to accept the results of a very complex general equilibrium model as input into a tool based on decision analysis. Second, the insight from GTAP is available only for the productivity change predictions of Rosenzweig and Parry (1994), not for the range of latest publications summarized in the IPCC's Fourth Assessment report. Third, general equilibrium models are an interesting tool to gather conditional information about the economy and interaction between sectors and regions. Or, as Jann Lay put it, general equilibrium models are useful as "a rather stylized, yet empirically underpinned, analytical tool to better understand the transmission channels of a shock through counterfactual analysis and approximate their relative importance." (Lay 2006: 142) They are usu-

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[1] Welfare losses that accrue in all sectors of the economy are compared to the gross agricultural product only. This may appear debatable, even though only those impacts from other sectors which were caused by yield productivity changes in the agricultural sector were considered. It is not problematic here as the numbers are not used for further modelling, but just to check whether the theoretical statements about the rough relative size of different dimensions of productivity changes, yield changes, and welfare changes in the agricultural sector are reflected in the GTAP-model.

ally no adequate tool to provide precise forecasts or precise numerical estimates of a certain policy change (Lay 2006: 142). This statement is supported by an empirical analysis of the forecast quality of GTAP: Without further adaptation of the GTAP parameters, the accordance between model predictions and actual changes was only 0.2 in a back casting exercise (Gehlhar 1997: 359).

A third obstacle to measuring the welfare impacts of climate change as the change of consumer and producer surplus was mentioned: The demand of a significant number of people does not materialize in the food markets. These people do not have enough money to buy the food they need. Therefore, the consumer surplus as calculated from market data, although difficult to assess, does not even describe the welfare effects of climate change correctly. It is an ethical question, whether the needs of people who can not buy in the markets are to be reflected in the assessment of the costs of climate change. The issue hinges on the usual concept of "willingness to pay" as a measurement for utility. The demand function in the economic graphs above reflects only, what people are willing to pay for food in the markets. For hungry people, an additional unit of food would have a high benefit for their well-being. But unless they have the money to buy food in the markets, this benefit does not affect the demand curve or the consumer benefit shown under the curve. The willingness to pay is closely related to the ability to pay. In the graph, the welfare of rich people automatically has a greater bearing on the consumer surplus as calculated from market data. It generally affects the validity of the willingness to pay principle in welfare assessments of whole societies and is not a specific problem of cost-benefit analysis of climate change. How to deal with this ethical question, should be for the problem owners to decide.

If the concept of basic human rights is to have validity, it is hard to argue that the welfare of some people is dramatically more important than the welfare of other people. Furthermore, in the political arenas of democracies the principle 'one person – one vote' implies the notion that all human beings are equally important. Food markets being linked to basic nutrition and thus survival suggest a link between the welfare considerations here and the discussion of the Declaration of Human Rights further down in chapter 7.2.3.

A default working assumption for this ethical issue is necessary, and in the following it is assumed that ex ante the welfare of all human beings is considered equally important, independent of their original riches. It is important to stress that this is an ethical assumption. If problem owners disagree with it, they should not accept the following considerations. If, for example, willingness to pay is considered the best measure for welfare, the changes in consumer and producer surplus valued at market prices are the best measure for the impacts of climate change.

To avoid that the welfare of rich people counts dramatically more than the welfare of poor people, the concept of equity weighting was introduced in many integrated assessment models of climate change (e.g. European Commission 1999: chapter 6; Azar and Sterner 1996; Tol 2002a; Clarkson and Deyes 2002). The usual concept for equity weighting is to value impacts of climate change at their local market value and then multiply the impacts in each region by a factor that expresses the ratio of the region's per capita income to the world's average per capita income. The philosophy behind the concept is, that willingness to pay as derived from market behaviour is a good basis for the valuation of impacts, but that one dollar is worth a lot more to a poor person than to a rich person. Therefore the impacts to a poor person counted in dollars are valued higher in a model with equity weighting than an impact to a rich person that has the same price in dollars. The formula for equity weighting is to multiply the regional impacts by the factor:

$$\left(\frac{Y_{world}}{Y_{region}}\right)^{-elasticity} \tag{6.3}$$

where Y is the GDP per capita and 'elasticity' is the elasticity of marginal utility of consumption with respect to income (Hope 2008a: 1015).

But even this form of equity weighting is no sufficient tool to guarantee that the well-being of all people is equally reflected in the calculations. First, only income differentials between regions are considered, not within regions. This may be a serious misrepresentation of reality, especially as the poor within the regions are expected to be hit hard by climate change (Adger et al. 2007: 727; Braun 2007: 10).

Second, where food for basic nutrition for the poor is concerned, part of the welfare changes are not shown at all in the changes of consumer surplus. Most of the world's poor are net food buyers (Grebmer et al. 2008: 27) and the FAO expects that in the future developing countries will increasingly need to rely on food imports (Bruinsma 2003: 77; cf. Watsa 2009: 3; Braun 2007: 10). The higher food prices rise due to climate change, the more people are driven out of the market because they can not afford the food they need. Consequently, they do not contribute to food demand in the markets and they disappear from the demand curve in the graph. The FAO also describes this phenomenon: potential demand for food is not expressed fully as effective demand when poverty does not allow people to buy or produce the food they need (Bruinsma 2003: 57). Appallingly, in the supply and demand curve shown above, it appears as if their welfare didn't count – and

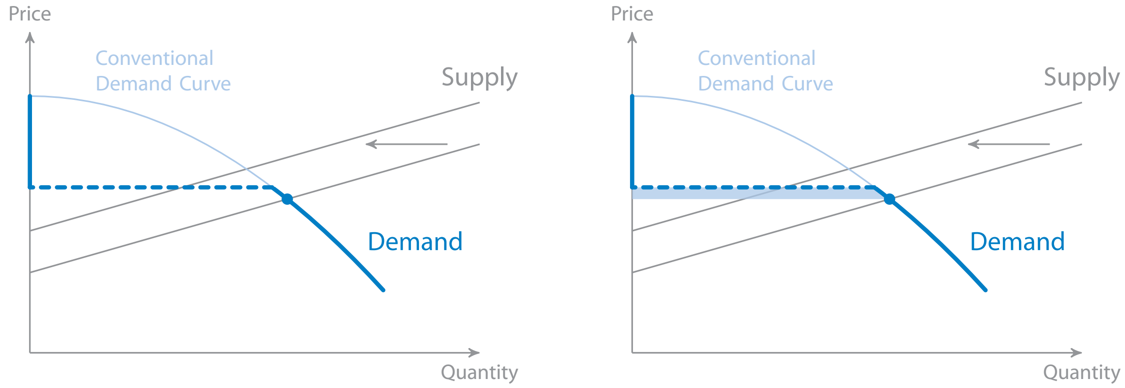

Figure 6.7: Demand curve of very poor people – and the impact of productivity losses

even in a calculation with equity weighting they may easily be forgotten, unless this phenomenon is carefully accounted for: an impact valued at zero remains at zero even after the application of equity weighting.

This is especially true for subsistence farmers who do not trade in markets but rather live on their own products. They do not appear in the demand or supply curve. If climate change causes yield losses to these subsistence farmers, the lost production obviously had a value to them – otherwise they would not work hard to produce their yields. But as the consumer surplus of the subsistence farmers never appeared in the demand curve produced from empirical market data, the loss of the benefit doesn't appear in the graph either. Equity weighting does nothing to correct for this omission, as long as global equilibrium models based on supply and demand curves are the basis of the assessment. The conventional approach to measuring consumer benefit is blind to the losses of subsistence farmers – although these losses may cause severe hunger, suffering and even death, and can hardly be called negligible. The issue is all the more relevant, as yield losses are projected to be high in developing countries, where subsistence farming still plays an important role (FAO n.y.: 2).

Figure 6.7 is like a magnifying glass that shows the corresponding demand curve of very poor consumers, who can not afford to buy enough food to meet their basic nutritional needs.

Like all macroeconomic graphs, the figure above is highly stylized. But it shows a few important features of food demand of the very poor, who are simply not able to pay higher prices and drop out of the market all together. Therefore the quantity they buy drops to zero when the prices surpass a certain level. The dashed line indicates this collapse of demand, rather than being a conventional demand curve. But in principle the result would be the same for a very flat demand curve. The price elasticity of demand is a lot bigger for these very poor people than for the rich, who reduce other expenditures before they seriously cut back on food consumption. The graph indicates that a considerable loss in productivity or even a complete breakdown of agriculture with 100% yield losses would lead to a reduction of consumer surplus to this population group only of the size of the light blue area in the right-hand graph. This is because, according to the conventional definition, the consumer surplus before the productivity losses was no bigger than this. Theoretically, the consumer surplus can be even smaller and approach zero, if the ability to survive is only just given at market prices.

Even if the willingness to pay were a good measurement of the welfare, the concept would not work in this context. The concept overlooks, that a starving person can not spend the money that was formerly spent on food on other items, once the ability to provide enough food for survival is lost. Therefore the loss of the utility of the food consumption is not compensated by any other gain. This is usually different: For example someone might decide to buy a fancy dress, then finds out that the dress is slightly more expensive than expected and doesn't buy the dress after all. This shows that the consumer surplus of the dress at the lower price was very small already and declines to zero at the higher price. The consequence of the higher price is, that the person misses the utility of the fancy dress, but also saves the money that would have been spent on the dress and buys something else with it, say a weekend trip. But this reasoning does not apply to people who are starving. Obviously, once they are dead, they can't by anything else with the money, which they did not spend on food. And even if the lack of food does not lead to death, it is a very serious welfare impediment. It is not correctly measured by a small ability to pay for sufficient nutrition – even if equity weighting adjusts the results for the average regional per capita income. It would be cynical to use the concept of consumer surplus as a measurement for welfare without further corrections. For all these reasons, people at risk of hunger are specifically included in the impact analysis in the next section.

Figure 6.8 is an attempt to illustrate the effect of the assumption that the absence of hunger is equally important for every person and that every person should count equally in the welfare considerations.

The original demand curve on the left shows the demand that is reflected in markets and conventional economic models. If the absence of hunger is to be taken as equally important no matter which person is affected, the demand curve needs to reflect the utility of food to those who do not or not fully satisfy their needs

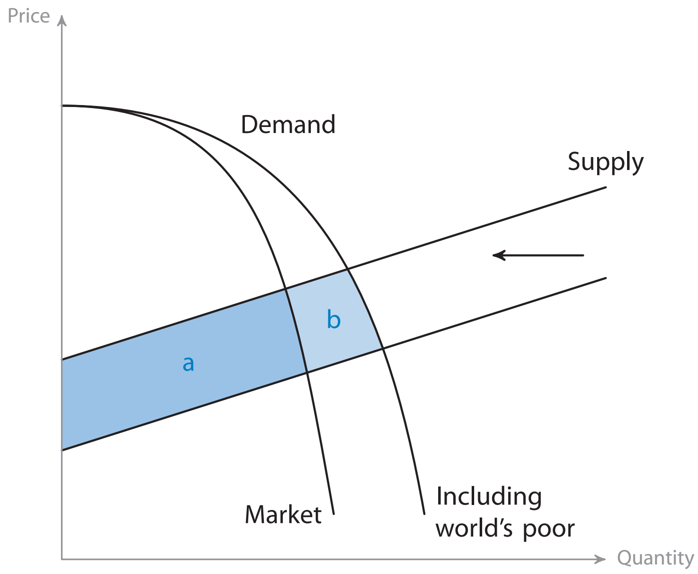

Figure 6.8: Insufficiency of welfare change assessments based on a demand curve retrieved from market data if the welfare of all humans is to be taken into account

in the markets. The adapted demand curve therefore reflects additional demand and moves to the right. If the supply curve moves to the left due to productivity losses, the change in consumer and producer surplus is now equal to the area $a + b$, whereas it was only the area a with the conventional demand curve. However, it is impossible to derive such a demand curve including the world's poor, or at least it was not done in any of the global equilibrium studies cited above.

And even the graph above does not entirely reflect the equality-assumption that the welfare of every human being should be given the same importance. In the graph, it is implicitly assumed that the food consumption with the lowest consumer surplus is driven out of the market before any other food consumption. In reality, there are two reasons why the willingness to pay for food may appear to be comparatively low for parts of the demand curve: first, luxury food consumption is affected that can be given up without a very significant welfare effect. Second, the ability to pay more is not given. If consumption of the first kind is lost, it can be assumed that the utility lost is no greater than the consumer surplus shown under the demand curve in the graph. If food consumption of the second kind is lost, it is logically consumption with a high utility, consumption that avoids starvation. Therefore part of the consumer surplus lost is in reality from the left of the graph, not from the right end of the consumer surplus triangle. Figure 6.9 illustrates the point:

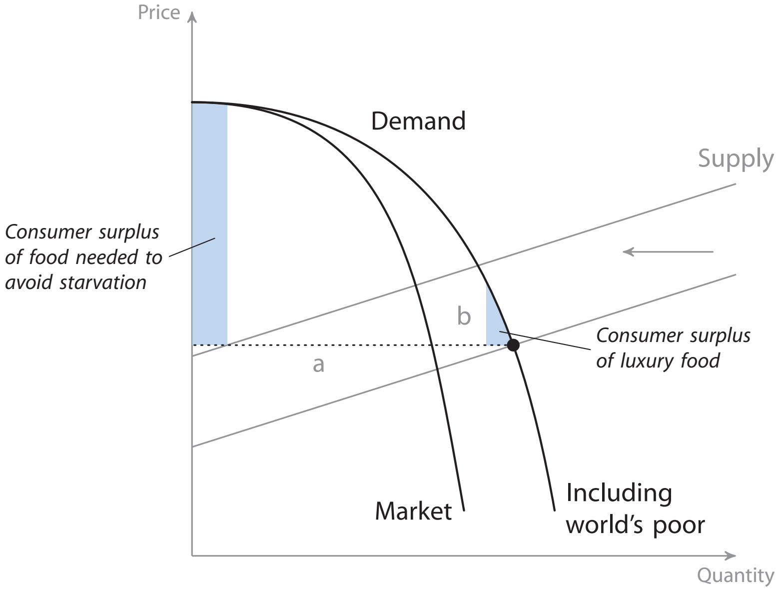

Figure 6.9: Valuation of welfare changes of two different types of demand reduction induced by rising prices

For all the above reasons, the determination of the change in consumer and producer surplus with global equilibrium models to measure the welfare consequences of productivity losses in the agricultural sector are not deemed appropriate for the purpose of this chapter. With a similar reasoning, Cline (2007: 32f) generally rejects the notion of incorporating the induced effects operating through international trade in the welfare assessment of climate change impacts in the agricultural sector. He argues foremost, that agricultural losses are expected to be severe in poor countries, and these poor countries do not have the financial means to buy food on the world market instead. Therefore the 'adaptation-option' that production is moved to countries that are less adversely affected is not realistic. He also points to the fact that yield losses are a poor indicator for the losses in consumer welfare, as was shown earlier in this chapter. In his assessment of the impacts of climate change, he multiplies the productivity losses by the price of the product (see Cline 2007: table 5.8). That is, he suggests not to calculate the new market equilibrium with climate change, but rather use the change in production quantity that would arise at stable prices as a basis for the quantification of impacts. Figure 6.10 illustrates this proposal.

With this approach, the area of the blue/dashed rectangle in figure 6.10 serves as an approximation of the welfare loss. Again, not the consumer and producer surplus (grey shaded quadrangle shows the consumer and producer surplus realised in

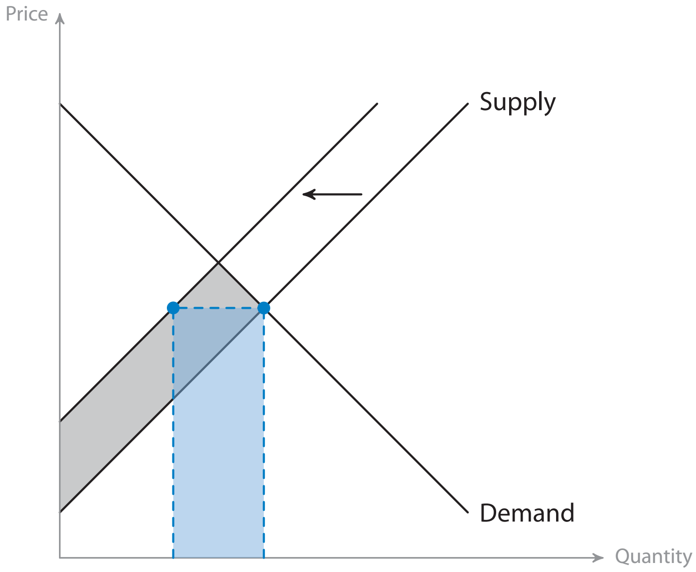

Figure 6.10: Valuation of welfare losses as in Cline 2007

the markets only) are measured. The method ignores the potential positive effects when prices and quantities were to rise to the new equilibrium point and indirect effects on other sectors. In the IPCC Fourth Assessment Report, it is written that global trade tends to reduce the overall projected climate change impacts on agriculture (Easterling et al. 2007: 284). This is not reflected in the method suggested by Cline not to include induced effects operating through international trade in the welfare assessment of climate change impacts in the agricultural sector. But in the same paragraph in the IPCC Report, it is also underlined, that negative impacts on agriculture can be expected to be especially severe in poor countries (Easterling et al. 2007: 284). The people there can not simply buy on the world markets whenever their yields fail, therefore Cline's critique of including global trade is relevant.

In light of the difficulties attached to alternative valuation procedures, the method suggested by Cline is used as a default option. On the one hand, this might be an overestimate of the true impacts, as in contrast to the change in consumer and producer surplus the positive effects of the prices rising to a new equilibrium are ignored. On the other hand, considering that the poor's benefit from food is not sufficiently reflected in the traditional demand curve, the grey shaded area in the figure above would almost certainly be an underestimate of true impacts. The numerical comparison of the order of magnitude of different measures based on model calculations by Tsigas et al. (1997) and presented in table 6.8 above suggest

	Market impacts (% of GAP)		
Warming	**Mean**	**5th percentile**	**95th percentile**
1.0 °C	6.1 %	2.3 %	9.6 %
2.5 °C	−5.4 %	−13 %	1.5 %
3.6 °C	−15 %	−23 %	−6.4 %
4.0 °C	−19 %	−28 %	−11 %
4.4 °C	−23 %	−32 %	−15 %
5.0 °C	−30 %	−40 %	−21 %

Table 6.9: Change in global gross agricultural product for different levels of global warming (positive numbers are gains)

	Market impacts (billion US$$_{2000}$/year)		
Warming	**Mean**	**5th percentile**	**95th percentile**
1.0 °C	159	60	249
2.5 °C	−140	−330	39
3.6 °C	−379	−598	−168
4.0 °C	−494	−716	−284
4.4 °C	−609	−833	−401
5.0 °C	−782	−1041	−540

Table 6.10: Market impacts of climate change in the agricultural sector

that the method chosen here is no overestimate of the true welfare impacts, even when the neglected food demand of the poor is not considered. However, the assessment by Tsigas et al. was done for a different purpose and can not be taken as a reliable numerical result for the context here. The valuation method of the impacts in the agricultural sector remains a subjective assumption.

6.4 Results for welfare impacts in the agricultural market sector

According to the methodology developed above, it is assumed that a proportion of GAP proportional to the productivity losses identified above is lost due to global warming. Tables 6.9 and 6.10 summarize the results. Results are for annual impacts.

To project the impacts of agricultural yield changes on GDP in general is even more difficult, because the future development of the share of agriculture in the overall economic production is unknown. In the past, this share was declining, but the trend may be slowed or stopped by rising prices for agricultural commodities

	Market impacts (% of GDP)		
Warming	**Mean**	**5th percentile**	**95th percentile**
1.0 °C	0.3 %	0.1 %	0.5 %
2.5 °C	−0.3 %	−0.6 %	0.1 %
3.6 °C	−0.7 %	−1.1 %	−0.3 %
4.0 °C	−0.9 %	−1.3 %	−0.5 %
4.4 °C	−1.1 %	−1.5 %	−0.7 %
5.0 °C	−1.4 %	−1.9 %	−1.0 %

Table 6.11: Change in global GDP due to climate change market impacts in the agricultural sector (positive numbers are gains)

in the future. In absence of more accurate data, the impact figures from table 6.9 for impacts as a percentage of GAP are multiplied by the share of GAP in GDP in the calculations above, 4.77%. This corresponds to a change of GDP as displayed in table 6.11.

The global average masks a wide difference between countries. Some nations will experience severe economic losses due to agricultural yield declines caused by climate change. For example in Côte d'Ivoire, agriculture contributes 26% to the overall GDP, and more than 50% of the country's aggregate export earnings (Bruinsma 2003: 111). This economic vulnerability exacerbates the risks of climate change, which are severe for the region in question. An increase in droughts is expected (Easterling et al. 2007: 280), and losses caused by sea-level rise are likely due to the coastal position of the country (cf. Nicholls et al. 2007: 324).

6.5 Discounting and equity weighting

In PAGE, all impacts are discounted according to the prescriptive discounting approach, that is with a discount rate that consists of the pure rate of time preference and an element representing the role of economic growth. The latter is the product of the per capita economic growth rate and the negative of the elasticity of the marginal utility of consumption. However in PAGE, as all impacts are given as a percentage of GDP, the impacts are also assumed to be bigger in a future world with a higher GDP. This is in line with discounting theory as presented for example by Rabl (1996: 143).

As impacts in PAGE are calculated as a percentage of the overall GDP, whereas the per capita GDP growth rate is reflected in the discount rate, GDP growth that is caused by growing population can actually increase future damages. It is in line with theory to use per capita economic growth in the discount rate as the aim is to ascertain the marginal utility of consumption, which is a measure of per capita growth, not overall GDP growth. Therefore, the main factor which leads to future impacts being valued less than current impacts in PAGE is the pure rate of time preference. Its standard setting in PAGE2002 is between 1% and 3%.

To apply the discounting concept of PAGE to the market impact results above, the rate of pure time preference is an ethical choice about which no singularly possible recommendation can be given here. For an analysis of the point see chapter 5.4.

As for the part of the discount rate accommodating the effects of economic growth, it remains to be assessed whether the market impacts in the agricultural sector really increase over time at the same speed as GDP will increase. In the previous sub-chapter, it was explained that assumptions about the future fraction of the gross agricultural product from GDP are rather speculative. In the past, this percentage has been declining (World Bank 2009a). But a growing world population or growing per capita consumption in some regions of the world can strongly increase the prices for agricultural products as demand and supply in this sector are rather inelastic (Braun 2007: 5). At the same time agricultural production is increasing to meet growing demand, but it is unclear whether supply can grow fast enough to feed the growing population. Climate change itself is expected to have an important influence on overall yields and thus the prices of agricultural products (Easterling et al. 2007: 297). The use of agricultural products in the energy sector further influences the market. (Braun 2007: 6f)

It is therefore considered not unreasonable to maintain the usual assumption of PAGE that climate change impacts can be given as a fraction of GDP. When it is expected that the contribution of GAP to GDP continues to decrease, this should be reflected in the model.

The use of equity weighting can be expected to have a significant effect on the final result. The regional examples given above show that the global results hide a strong regional difference in the effects of climate change on agriculture. To capture these regional differences in equity weighting, a much smaller regional resolution would be necessary than can be given in this dissertation – or is established in the PAGE regions. Therefore it is recommended to apply equity weighting, but also to keep in mind that equity weighting in PAGE can not capture all regional extremes.

People at risk of hunger due to climate change

7

The welfare changes caused by a change in the number of undernourished and starving people are not sufficiently reflected in the compilation of market impacts (see chapter 6.3). Other non-market impacts in the agricultural sector are possible negative effects of a loss in biodiversity or impacts on traditions linked to agriculture. Biodiversity is often treated as a separate impact category in integrated assessment models. Very little is known about possible repercussions on culture in societies that are strongly characterised by agriculture. In this chapter, the effect of climate change on people at risk of hunger is explicitly assessed. For this task it is necessary to project the additional millions at risk of hunger due to climate change, and to value the corresponding welfare changes in the PAGE model.

7.1 Projections of additional millions at risk of hunger

It is not easy to project the additional millions at risk of hunger as the uncertainties attached to the effect of climate change on global hunger are very large. The baseline development of hunger without climate change has a huge influence on how hard the poor of the world will be hit by climate change. Among the important factors are: biofuel production, population growth, income inequality development, economic growth, urbanisation, and investment in agricultural research (cf. Braun 2007). Confronted with all these and other factors that strongly depend on policies which will be adopted in the future and are hard or impossible to predict, it becomes painfully clear how unreliable forecasts of the effects of climate change on hunger must be. The uncertainties around the prediction of climate change and its local effects have not even been mentioned so far.

Maybe a small reduction in overall uncertainty can be derived from the fact, that two effects of uncertain future economic growth actually push the number of people at risk of hunger into different directions: On the one hand, economic growth leads to increasing purchasing power of the poor, if the benefits of the boom are not confined to the wealthier parts of the societies. This indicates a reduction in millions at risk of hunger. On the other hand, increasing wealth in low-income countries leads to rising food demand and thus rising food prices – bringing those who do not profit equally from economic growth into even greater difficulties (Braun 2007: 1f). An example for this effect is the recent five year price boom from 2003 to 2008. Between 130 million and 155 million people have been pushed into extreme poverty by the high food prices according to estimates from the World Bank (Watsa 2009: 5). Higher food prices in 2008 alone may have increased the number of children with permanent cognitive or physical injury due to malnutrition by 44%. Poverty rose most in East Asia, the Middle East and South Asia. The effect on Africa was less pronounced, as food prices in Africa rose less and more people live in rural areas (Watsa 2009: 5). Interesting in the context is that on average the world's poor are to a substantial extend net food buyers (Braun 2007: 10).

7.1.1 Data basis

In the IPCC Fourth Assessment Report, numbers for people at risk of hunger with and without climate change are given (see table 7.1). The first set of rows in the table depicts reference projections under SRES scenarios and no climate change. The second set (CC) includes climate change impacts, based on Hadley HadCM3 model output, including positive effects of elevated CO_2 on crops. The third (CC, no CO_2) includes climate change, but assumes no effects of elevated CO_2. Projections from 2020 to 2080 are given for two crop-modelling systems: on the left, AEZ (Tubiello et al. 2007); on the right, DSSAT (Parry et al. 2004), each coupled to the same economic and food trade model, BLS (Fischer et al. 2002, 2005). The models are calibrated to give 824 million undernourished in 2000, according to FAO data. (Easterling et al. 2007: 299)

In Fischer et al. (2005: 2080), results are given for additional under-nourished due to climate change in a SRES A2 scenario as a function of the atmospheric CO_2-concentration. Figure 7.1 shows this relationship.

The data from Tubiello et al. cited in the IPCC Fourth Assessment Report was actually derived with the same model as this graph. Fischer was a main author in both publications. It is interesting to check what may cause the differences in the results. Contrary to the numbers cited in Easterling et al. based on the climate model HadCM3 only, the numbers from Fischer et al. (2005) are derived via simulations with both HadCM3 and CSIRO climate projections. Therefore the

	2020 Millions at risk		2050 Millions at risk		2080 Millions at risk	
Scenario	**AEZ-BLS**	**DSSAT-BLS**	**AEZ-BLS**	**DSSAT-BLS**	**AEZ-BLS**	**DSSAT-BLS**
Reference						
A1	663	663	208	208	108	108
A2	782	782	721	721	768	769
B1	749	749	239	240	91	90
B2	630	630	348	348	233	233
CC						
A1	666	687	219	210	136	136
A2	777	805	730	722	885	742
B1	739	771	242	242	99	102
B2	640	660	336	358	244	221
CC, no CO_2						
A1	n/a	726	n/a	308	n/a	370
A2	794	845	788	933	950	1320
B1	n/a	792	n/a	275	n/a	125
B2	652	685	356	415	257	384

Table 7.1: Numbers for millions at risk of hunger as given in (Easterling et al. 2007: 299)

data may differ slightly from the numbers in Easterling et al., even if Fischer was also the main author of one of the model combinations displayed there. But the AEZ-model results from the two different sources should be close enough for the Fischer et al. (2005: 2080) data to be a useful complement to the results reported in the IPCC's Fourth Assessment Report. In the article by Fischer et al., numbers for transient temperature rise are given as a function of CO_2-concentration up to 830 ppm, not just for three point estimates. Furthermore, no distinction in projections with and without CO_2-fertilization is given, but just results with CO_2-fertilization.

7.1.2 SRES storyline

The PAGE2002 model in its basic form is calibrated to the IPCC SRES (Special Report on Emissions Scenarios) scenario A2. The A2 storyline describes a very heterogeneous world with emphasis on local identities. Economic development is therefore regionally oriented and per capita economic growth and technological development are rather fragmented and slower than in other storylines. Fertility patterns across regions converge very slowly, which leads to high population growth. (IPCC 2000: 5) In 2100 the A2 scenario assumes a global population of 15

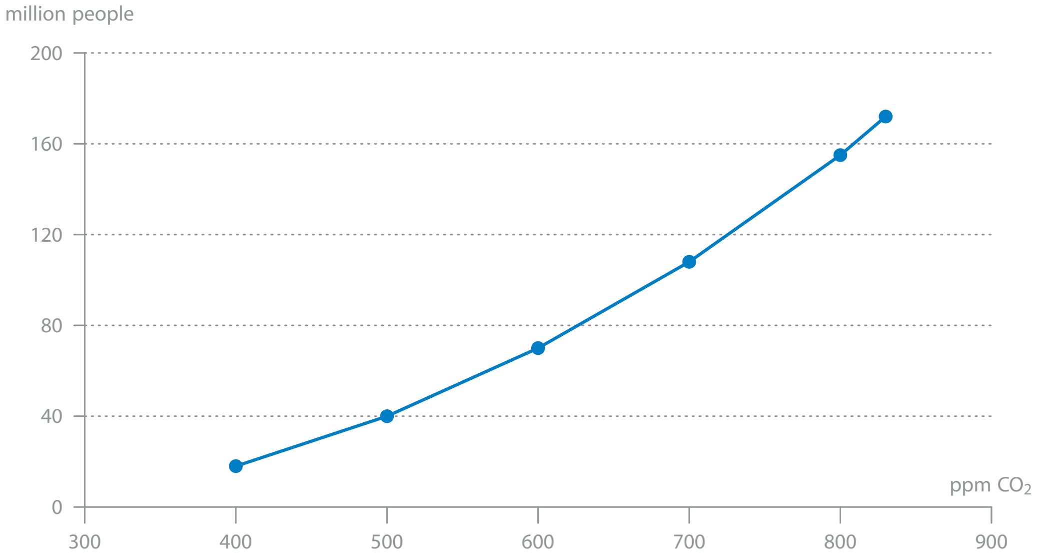

Figure 7.1: Additional millions at risk of hunger as in Fischer et al. (2005: 2080)

billion (IPCC 2000: 13). Numbers for the following century are not given by the A2 scenario, but in PAGE2002 it is assumed that population growth does not stop in 2100 and the global population reaches 20 billion in 2200.

It is debatable whether A2 is the best scenario to use. In the IPCC Special Report, emphasis is put on the statement, that there is no single best guess scenario (IPCC 2000: 11). The population growth in A2 is considerably higher than in current UN projections (UN 2004: 1). The greenhouse gas emissions are also rather high compared to other SRES scenarios (IPCC 2000: 7). Recent developments suggest this may be an underestimate rather than an overestimate: The fossil fuel emissions development over the last year tracked the emissions of the most carbon-intensive of all SRES scenarios (Global Carbon Project 2009: 14). In this context, the low-emission scenario B1 could hardly be called a business-as-usual model. Thus, the choice of A2 as the underlying scenario in PAGE is defensible. Furthermore it would be beyond the scope of this dissertation to apply a different scenario to PAGE. Therefore in the following, hunger projections for A2 are used as the basis of analysis.

7.1.3 Extracting a suitable probability distribution function from the available data

7.1.3.1 Data from Easterling 2007

In table 7.1 above cited from Easterling et al. (2007: 299), estimates for the millions at risk of hunger are given from two different crop models: DSSAT (Parry et al. 2004) and AEZ (Tubiello et al. 2007). They use different approaches to quantify millions at risk of hunger. In Parry et al., the measure 'risk of hunger' is based on the number of people whose incomes do not allow them to purchase sufficient quantities of cereals. It therefore depends on the price of cereals and the number of people at given levels of income (Parry et al. 2004: 65). Tubiello and Fischer rely on a strong empirical correlation between shares of undernourished and the ratio of average national food supply including imports (Tubiello and Fischer 2007: 1040).

The important knowledge gaps concerning additional millions at risk of hunger from climate change are stressed in the IPCC report. It is written that in most studies only the climate change impacts on food availability are captured, not those on the stability of food supplies. Furthermore, projections are based on a limited number of crop models, and only one economic model, the latter lacking sufficient evaluation against observations. (Easterling et al. 2007: 298)

Still, they are the best data available and are used in the following. It is fairly robust to deduce from the studies that climate change will increase the number of people at risk of hunger (Easterling et al. 2007: 298). Therefore an omission of this impact would certainly distort results from any cost-benefit model of climate change.

Both studies are calibrated to 824 million undernourished in 2000, according to FAO (Food and Agricultural Organisation) data. Thus, their projections should contain the same group of people as official FAO data. More recent FAO numbers (FAO 2008b) reveal 963 million undernourished, with 37 million dying from the consequences of hunger every year (Ziegler 2009). This means, that 3.8% of the undernourished died from the consequences of hunger. In the absence of better data, it is assumed that this proportion will remain valid in the future.

The estimates of millions at risk of hunger in Easterling et al. (2007: 299) are given for three different scenarios: (1) a reference scenario without climate change, (2) a scenario with climate change and CO_2-fertilization, and (3) a scenario with climate change but no CO_2-fertilization effect. The additional millions at risk of hunger are the difference between the hungry people in the baseline scenario and the undernourished in the scenario with climate change.

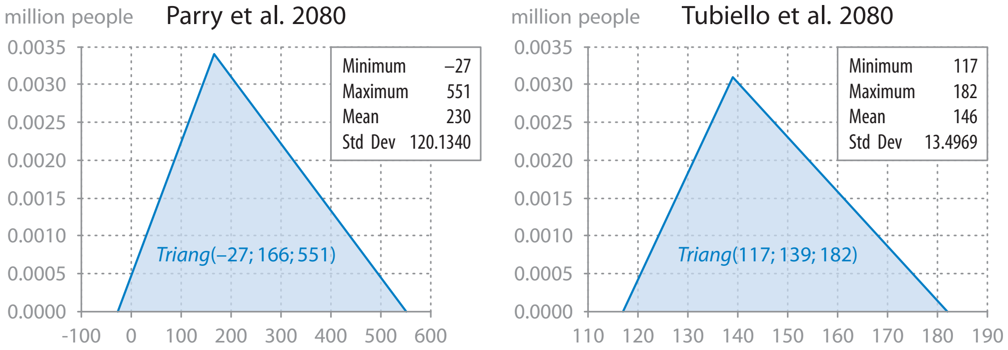

Figure 7.2: Probability distribution functions for the additional millions at risk of hunger due to climate change derived from data in Easterling et al. (2007: 299)

As described in chapter 2.6, the scientific debate is still open as to how strong the CO_2-fertilization effect will be. Therefore, both the results with and without CO_2-fertilization are taken into account. A probability distribution function is chosen so as to cover the range between the two values as well as a rough representation of different likelihoods of the values covered. The difference between the reference scenario and the scenario with climate change but without CO_2-fertilization is taken as the upper limit of this probability distribution function describing the additional millions at risk of hunger due to climate change. Correspondingly, the difference between the reference scenario and the scenario with climate change and CO_2-fertilization is taken as the lower limit. No information is available about the suitable form of the probability distribution function. Therefore, a simple triangular distribution is chosen as a distribution with clearly defined upper and lower limits and less likelihood attached to extreme values. As some CO_2-fertilization seems likely to occur, the most likely value is chosen closer to the value with CO_2-fertilization. The difference between the number with CO_2-fertilization and the most likely value is assumed to be one third of the whole range covered by the probability distribution function. This is a conservative estimate as not only CO_2-fertilization is uncertain, but a range of other factors have not been sufficiently included like extreme weather events, flooding, sea-level rise, or pests and problematic soil conditions (Fischer et al. 2005: 2072; Parry et al. 2004: 57; Lotze-Campen 2009).

Figure 7.2 illustrates the corresponding probability distribution functions for the results from Parry et al. and from Tubiello et al. for the year 2080. Corresponding probability distribution functions are developed for 2020 and 2050.

It is important to note that these probability distribution functions do not cover the whole range of possible values. Rather, they describe the best guess values from the corresponding studies taking into account just one reason for uncertainty: the unknown intensity of CO_2-fertilization. All other sources of uncertainty would further widen the range covered by the probability distribution functions. No data is available on a numerical assessment of these uncertainties. They are not included in the calculations of this chapter. The results can therefore only indicate the order of magnitude and not deliver exact results, and even for this very reduced probability distribution functions the uncertainties are large.

A subjective appraisal of these uncertainties can be done at a later point of the assessment, without reducing the transparency of the following calculations.

7.1.3.2 Data from Fischer et al. (2005)

In the second source for additional millions at risk of hunger cited above (Fischer et al. 2005: 2080), different point estimates for the people at risk of hunger from the two climate models used are given in a graph. From these point estimates, the authors derive a likely polynomial function of additional millions at risk of hunger at different greenhouse gas concentrations in the atmosphere. No information is given about a likely range of results. Therefore values from this polynomial function are used as a best guess in the following calculations. This does not contradict the PAGE philosophy of presenting impact numbers as probability distribution functions, because the data based on Fischer et al. (2005) is mainly used as an extra piece of information to achieve a more reliable interpretation of the data taken from the IPCC report.

7.1.4 Risk of hunger as a function of temperature change

The estimates in Easterling et al. (2007: 299) are given for three different points in time: 2020, 2050 and 2080. Results in Fischer et al. (2005) are given as a function of atmospheric CO_2 concentrations. In PAGE, impacts are expressed as costs that occur at a given temperature change. Therefore the results above need to be converted to this form.

The global temperature rise in the SRES-scenarios is given in ten-year intervals (IPCC 2001: 824). Equally, the CO_2-concentration in the atmosphere for the A2 and other scenarios are given for different models. The corresponding relationship between time, greenhouse gas concentration and transient temperature change compared to 1990 from the ISAM model, reference case (IPCC 2001: 807) is given in table 7.2.

Year	CO_2 concentration in the atmosphere (ppm)	Transient surface air temperature change above 1990	Transient temperature rise above preindustrial
1970	325	–	–
1980	337	–	–
1990	353	0.00	0.33
2000	369	0.16	0.49
2010	390	0.35	0.68
⋮	400	0.41	0.74
2020	417	0.50	0.83
2030	451	0.73	1.06
2040	490	1.06	1.39
⋮	500	1.15	1.48
2050	532	1.42	1.75
2060	580	1.85	2.18
⋮	600	2.02	2.35
2070	635	2.33	2.66
2080	698	2.81	3.14
⋮	700	2.82	3.15
2090	771	3.29	3.62
⋮	800	3.46	3.79
⋮	850	3.75	4.08
2100	856	3.79	4.12

Table 7.2: Development of CO_2-concentration and global average temperature in the SRES A2-scenario; rows without year indicate relevant concentration levels in between the years above and below (data from IPCC 2001: 807+824)

In Fischer et al. (2005: 2072) the relationship between temperature and CO_2-concentration in the atmosphere is given. The millions at risk of hunger are given as a function of CO_2-concentration. It may seem the most straightforward method to use these data as well as temperature projections from the same source to derive numbers for the millions at risk of hunger as a function of temperature. With this procedure, the detour over IPCC-SRES data with several slightly different model results is avoided, and the actual temperature-concentration used in the study could be reflected. However, several points need to be taken into consideration when comparing global warming figures from different sources. Table 7.3 gives an overview of the various characteristics that can differ as well as the properties

	Fischer 2005	SRES-TAR	PAGE
Baseyear/baseperiod	1961–1990	1990	pre-industrial
CO_2 only	no	no	no
Transient temperature	yes	yes	both
Land surface only	yes	no	no

Table 7.3: Comparison of characteristics of temperature rise estimates as a function of CO_2-concentration from different sources

ppm	Temperature change in A2 (TAR) adapted to PAGE baseline	PAGE transient temperature	PAGE equilibrium temperature
330	0.2	–	–
400	0.7	0.7	1.6
500	1.5	1.5	2.7
600	2.4	2.4	4.0
700	3.2	3.2	5.1
800	3.8	4.0	6.0
850	4.1	4.4	6.3

Table 7.4: Comparisons of A2-temperature projections in the IPCC-TAR and the PAGE-model

of global warming data from the IPCC's Third Assessment Report (IPCC-TAR), Fischer et al. (2005), and the PAGE model.

The base period taken as the time for which 0°C temperature change is assumed differs for all three sources. As the impact module shall be used in PAGE, other data needs to be adjusted to the base year in PAGE. All three sources include the global warming caused by other greenhouse gases as well. Both Fischer and the IPCC-TAR indicate transient temperature change; from the PAGE model both transient and equilibrium temperatures can be retrieved. In table 7.4 the transient temperature projections for the SRES A2 scenario as given in the IPCC-TAR and in the PAGE model are compared to the equilibrium temperature in PAGE. The equilibrium temperature is the temperature that would be reached in the long run if the atmospheric greenhouse gas concentration remained at the given level.

The transient temperature rise in PAGE is very close to the projections from the IPCC-TAR. Only for higher greenhouse gas concentrations, the temperature rises a bit faster in PAGE than in the IPCC-TAR. This could be due to saturation effects that may not be completely reflected in PAGE. The equilibrium temperature is obviously higher than the transient temperature.

In the following, the correlation between CO_2-concentration and transient temperature rise as derived from PAGE is used to convert the millions at risk of hunger in a certain future year to a measure dependent on temperature rise. Using this correlation from PAGE, possible inaccuracies in the temperature development in PAGE have no effect on the final model results: inaccuracies in the conversion of the results above to a measure dependent on temperature change and inaccuracies in the temperature development in PAGE cancel each other out. An example can illustrate this: If the theoretically "correct" temperature rise for 850 ppm CO_2 is 4.1°C whereas the PAGE value of 4.4°C is used, then the curve describing millions at risk of hunger per degree global warming is rising too slowly. The "correct" number of hungry people for 4.1°C is reached only further to the left in the graph, at 4.4°C. The impact of climate change is thus underestimated in the PAGE climate impact module. But when the PAGE model is run, temperatures rise a little bit too fast at high greenhouse gas concentrations, namely 4.4°C instead of 4.1°C. Impacts of climate change are overestimated by the same amount. The two "errors" cancel each other out.

It is correct to use transient temperature changes as these were the basis for the calculations in Easterling et al. (2007) and Fischer et al. (2005). Like this, the impact figures are truthfully converted to the metric used in the PAGE model maintaining the assumptions about the climate system from the original studies.

7.1.5 Recent scientific findings on temperature projections

In the IPCC Fourth Assessment Report, more recent knowledge on the relationship between CO_2-concentrations and global warming is available. Upper ranges for temperature rise are larger mainly because stronger climate-carbon cycle feedbacks are suggested by recent research (IPCC 2007a: 45).

A broad range of post-SRES scenarios has been published since 2000. The comparison of these scenarios is difficult for three reasons: some include non-CO_2 gases and some don't; in some scenarios the global temperature is not stabilized but declines after a peak; not all studies rely on the SRES socio-economic scenarios and therefore a broader range of underlying assumptions was used. Notwithstanding these difficulties, the IPCC categorized the post-SRES scenarios in six groups. (Fisher et al. 2007: 197) The results are displayed in table 7.5.

The global mean temperature levels indicated in table 7.5 are stabilization temperatures, not transient temperatures. They can therefore not be compared directly to the global warming levels given for the A2 scenario above. But it is possible

Cat.	**Additional radiative forcing (W/m^2)**	**CO_2-concentration (ppmv)**	**CO_2-eq. (ppmv)**	**Global mean temperature increase above pre-industrial at equilibrium**	**Peaking year for CO_2 emissions**	**Change in global emissions in 2050 (% of 2000 emissions)**	**Number of scenarios**
I	2.5 – 3.0	350 – 400	445 – 490	2.0 – 2.4	2000 – 2015	−85 to −50	6
II	3.0 – 3.5	400 – 440	490 – 535	2.4 – 2.8	2000 – 2020	−60 to −30	18
III	3.5 – 4.0	440 – 485	535 – 590	2.8 – 3.2	2010 – 2030	−30 to −5.0	21
IV	4.0 – 5.0	485 – 570	590 – 710	3.2 – 4.0	2020 – 2060	+10 to +60	118
V	5.0 – 6.0	570 – 660	710 – 855	4.0 – 4.9	2050 – 2080	+25 to +85	9
VI	6.0 – 7.5	660 – 790	855 – 1130	4.9 – 6.1	2060 – 2090	+90 to +140	5
						Total:	177

Table 7.5: Classification of recent (post-TAR) stabilization scenarios according to different stabilization targets and alternative stabilization metrics; (Fisher et al. 2007: 198)

to compare the equilibrium temperatures in PAGE with the figures above. Both sources indicate temperatures compared to the pre-industrial level, therefore no adjustments need to be made for the base year.

For the post-SRES scenario categories, the CO_2-concentrations are given as ranges rather than single values. In PAGE, the equilibrium temperatures are given for those years that are generally used for the assessment in the model. In table 7.6, CO_2-concentrations within the post-SRES ranges for which the equilibrium temperature is given are displayed as well as the post-SRES figures. The CO_2-concentration for PAGE is not always in the middle of the post-SRES ranges, this needs to be taken into account while comparing the PAGE figures with the ranges for temperature rise given in the post-SRES scenarios. Only for categories III and VI no adequate figures are available in PAGE, and the results displayed in the table were derived by a combination of linear interpolation and the application of a trend line function (all trend lines derived with the least-square-method).[1]

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[1] The trend function as given by Excel can be very unreliable where the quadratic term is multiplied with a very small number as is the case here (–0.000008). In such a case, the difference between –0.0000075 and –0.0000085 can have a very significant consequence on the result. In a similar case a calculation with help of the trend function led to a temperature change of –16°C instead of +1.4°C. But for higher temperatures where the calculation intervals in PAGE are larger, a simple linear interpolation is not correct either as the curve bends. For category III the results from both methods were close enough to lead to the same result when one digit after the point is specified. For category VI the results were 4.9 (trend function) and 5.1 (linear). These numbers are also close enough to rule out a serious misspecification and the average of 5.0 is used.

	AR4 post-SRES scenarios		PAGE model	
Category	**CO_2-concentration (ppm)**	**Equilibrium temperature rise**	**CO_2-concentration (ppm)**	**Equilibrium temperature rise**
I	350 – 400	2.0 – 2.4	391	1.5
II	400 – 440	2.4 – 2.8	419	1.7
III	440 – 485	2.8 – 3.2	455	2.2
IV	485 – 570	3.2 – 4.0	490	2.6
V	570 – 660	4.0 – 4.9	578	3.7
VI	660 – 790	4.9 – 6.1	700	5.0

Table 7.6: Comparison of temperature projections in the post-SRES scenarios and in the PAGE model; based on data from PAGE2002 and Fisher et al. (2007: 198)

Even though temperature ranges are compared with point estimates for a specific CO_2-concentration in PAGE, it is obvious that the more recent post-SRES scenarios project a significantly stronger warming for a given greenhouse gas concentration. For example the equilibrium temperature rise for 419 ppm CO_2 is 1.7°C, whereas the lower concentration range of 350–400 ppm CO_2 in the post-SRES scenarios is linked to a higher temperature rise of 2 to 2.4°C. The difference is smaller for higher concentrations, but this may be due to the larger uncertainty of those categories for post-SRES scenarios.

The yield change estimates and assessments of the effects of climate change on the number of people at risk of hunger as given in Easterling et al. (2007: 299) and Fischer et al. (2005: 2080) are mainly based on the earlier SRES scenarios. Therefore, the difference above between the SRES and the post-SRES scenarios does not affect the conversion of the impact figures to a function of temperature rise in the A2-scenario used in PAGE2002. It is correct to use the lower data from PAGE2002 based on the SRES scenario. The impact studies are foremost assessments of the relationship between physical impacts and a certain level of temperature rise. Only the CO_2-concentration affects the results via the effect of CO_2-fertilization. It is impossible to separate these two components of the impact studies here, and the relationship between temperature rise and physical impacts is in the following assumed to remain unchanged by the fact that global warming may occur faster for given levels of CO_2-emissions than previously thought. If an error is introduced by this simplification, it leads to an underestimate of the damages, as the CO_2-concentration and correspondingly the CO_2-fertilization effect is slightly overestimated at any given level of temperature rise. This further

	Parry et al.			Tubiello et al.		
Warming	**with CO_2-fertilization**	**best guess**	**no CO_2-fertilization**	**with CO_2-fertilization**	**best guess**	**no CO_2-fertilization**
0.87 °C	23	36	63	−5	1	12
1.75 °C	1	71	212	9	28	67
3.10 °C	−27	166	551	117	139	182

Table 7.7: Additional millions at risk of hunger, data for the A2 scenario (Easterling et al. 2007: 299) converted to levels of temperature rise in the PAGE model

supports the assumption above that the most likely results are not those with full CO_2-fertilization.

Whereas the impact module in PAGE is not affected by this knowledge update, the more recent information about the relationship between greenhouse gas concentrations and global warming should be integrated into the climate module. The findings above suggest that past estimates of the costs of climate change were rather an underestimate.

7.1.6 Results

For the projections from Parry et al. as given in the IPCC Fourth Assessment Report, the difference between the values with and without CO_2-fertilization is very big. For the projections from Tubiello et al., the difference between the two scenarios is far smaller. But the most likely values as defined above are rather similar, considering the uncertainties involved. Table 7.7 reports and figure 7.3 illustrates the results derived from the data in the Fourth Assessment Report. The scenario with full CO_2-fertilization is given in the lower curve, the scenario without CO_2-fertilization in the upper curve, and the middle curve describes the most likely value as defined above: As some CO_2-fertilization seems likely to occur, the most likely value is chosen closer to the value with CO_2-fertilization. The difference between the number with CO_2-fertilization and the most likely value is assumed to be one third of the whole range covered by the probability distribution function. All results are for annual impacts.

7.1.7 Extrapolation to higher temperatures

To make the results comparable to the figures from the previous chapter, the number of people at risk of hunger shall be given for the same levels of temperature rise as the market impacts in the previous chapter. This includes the task of inter-

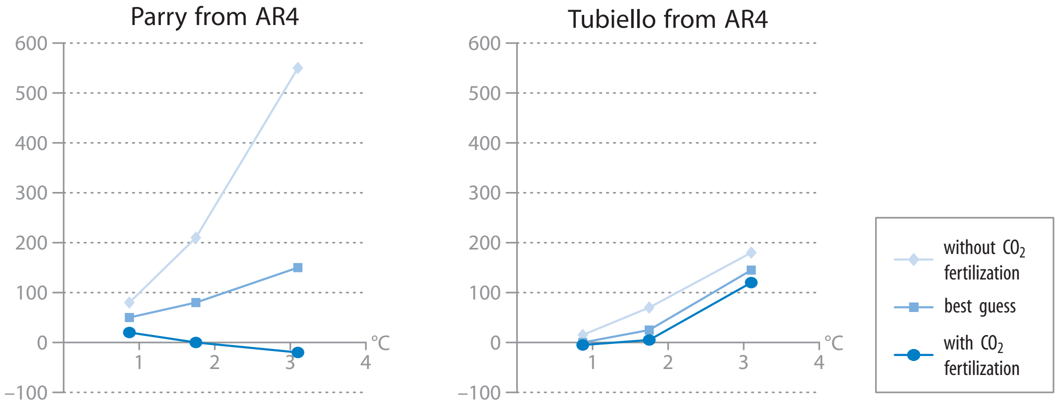

Figure 7.3: Additional millions at risk of hunger as a function of global warming; calculations based on data from the IPCC Fourth Assessment Report (Easterling et al. 2007: 299) and from the PAGE model

polation between two given points in the graphs above, and the more difficult task of extrapolation to higher temperatures.

A linear inter- and extrapolation seems rather crude and does not lead to a good fit for the few data points given. As another attempt, a polynomial trend function is fitted to the values. As a fourth calibration point, zero additional millions at risk of hunger at zero temperature change is used. It is obvious, that in the absence of climate change no additional people could face hunger due to climate change.

The data from these four points suggest that a polynomial trend function of the second order may be a good approximation of the relationship. The R^2 for five of the six relationships above is between 0.9947 and 0.995. Only the curve for the results by Parry with CO_2-fertilization has a lower R^2 of 0.8614 when approximated with a polynomial function of the second order. This is due to the relationship of the calibration point at (0,0) to the rest of the results: The three values given for the years 2020, 2050 and 2080 (or the corresponding levels of temperature rise) are a clearly falling sequence with the values for the number of additional people at risk of hunger switching from positive to negative. Figure 7.4 illustrates the relationship between the point values and the polynomial trend line for the lower value in Parry and for the best guess. The graph with the best guess is representative of the other four graphs that are not shown here.

The functions of the polynomial trend curves from the five graphs with high R^2 are used to calculate impacts for 1°C, 2.5°C, 4°C and 5°C warming; 4°C is introduced as an additional value as the difference between 2.5°C and 5°C is rather large, especially when no results are directly available for a temperature change higher than 3.1°C.

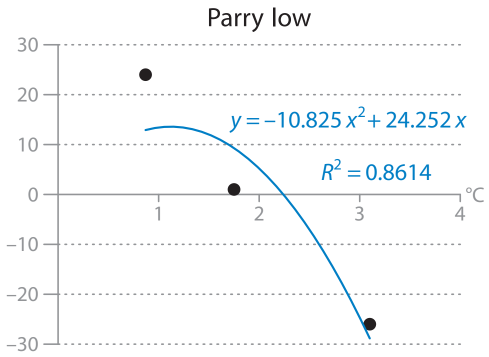

Figure 7.4: Trend line for the scenario with full CO_2-fertilization by Parry et al. (Easterling et al. 2007: 299)

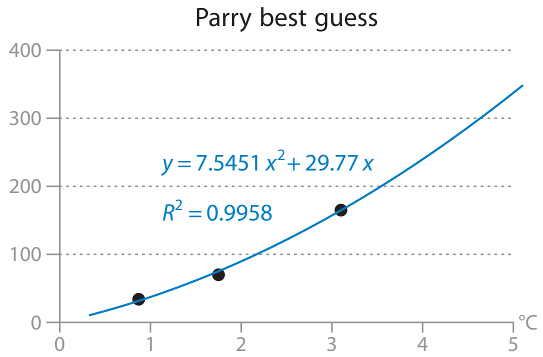

Figure 7.5: Trend line for the best guess based on numbers from Parry et al. (Easterling et al. 2007: 299)

	Parry et al.			Tubiello et al.		
Warming	**with CO_2-fertilization**	**best guess**	**no CO_2-fertilization**	**with CO_2-fertilization**	**best guess**	**no CO_2-fertilization**
1.0 °C	19.8	37.3	85.1	−8.9	1.4	22.6
2.5 °C	−14.6	121.6	378.8	60.5	80.9	121.6
4.0 °C	−15.0	239.8	871.8	229.2	253.3	298.7
5.0 °C	0.0	337.5	1311.2	396.9	419.8	460.1

Table 7.8: Additional millions at risk of hunger; own calculations on basis of the IPCC Fourth Assessment Report (Easterling et al. 2007: 299)

For the results with CO_2-fertilization from Parry et al., a polynomial function of the second degree simply is no appropriate approximation in this case. It is not in accordance with the general findings of chapter five in the Working Group II volume of the IPCC Fourth Assessment Report to assume that climate change will reduce the number of people at risk of hunger further and further with rising global temperatures. The very optimistic results for 3.1°C warming can not be interpreted as a general success in the fight against hunger until 2080, as in the reference scenario without climate change 769 millions at risk of hunger are expected. Therefore the polynomial trend function is ruled out. The figures for the 1°C and the 2.5°C warming are derived with linear interpolation. As a very optimistic scenario, it is assumed that at 5°C warming no additional people will suffer hunger due to climate change. The value for 4°C warming is assumed in between those for 3.1°C and 5°C. The results are displayed in table 7.8.

For the results from Parry et al., the best guess number of undernourished people for a 5°C warming is twice the value for a 3.1°C warming, the highest temperature change for which a direct result is available from the table in Easterling

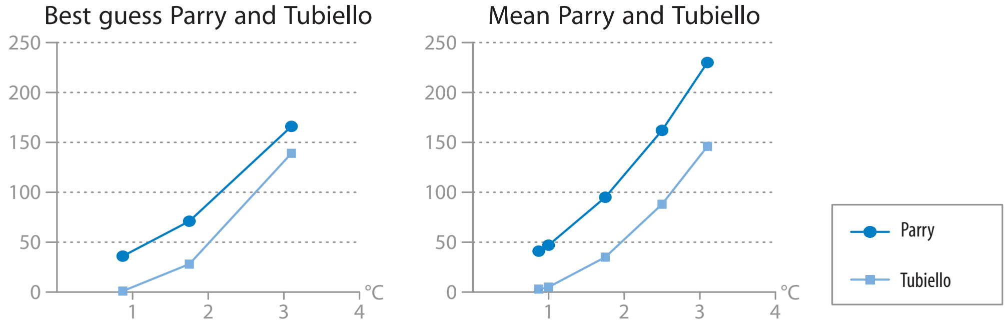

Figure 7.6: Comparison of polynomial trend lines when the calibration points are a) the best guess values or b) the mean of the triangular probability distribution function as defined above

et al. (2007: 299). For the results from Tubiello et al., it is even three times the 2080 value for a 3.1°C warming. This further demonstrates how much the results for higher temperatures depend on the functional form of the trend line, which is highly uncertain. Even the functional form is unknown. Figure 7.6 furthermore illustrates the difference in the polynomial trend line functions, when not the best guess values are taken, but rather the respective means of the triangular probability distribution functions for 2020, 2050 and 2080. Again a polynomial trend line is used for the interpolation.

For the best guess values, the estimate based on Tubiello et al. is getting closer to the estimate based on data from Parry et al. for higher temperatures. As was shown in table 7.8, the numbers for the 4°C and 5°C warming are even higher based on Tubiello et al. than those relying on data from Parry et al. This is different when not the best guess values (twice as close to the numbers with CO_2-fertilization than to the numbers without CO_2-fertilization) but the respective mean values of triangular probability distribution functions with the following specification are interpolated: lower bound = value with full CO_2-fertilization; best guess = best guess as defined above; upper bound = value without CO_2-fertilization. In the right part of figure 7.6 it becomes clear, that the estimates based on the two different sources drift further and further apart for higher temperatures. This is confirmed by the mathematical calculation of the estimates for higher temperatures.

The reason for this difference is the high disparity of the results by Parry et al. with and without CO_2-fertilization (cf. figure 7.3). While for the results without CO_2-fertilization the number of people at risk of hunger rises very fast, for the scenario with full CO_2-fertilization the results by Parry et al. even suggest that climate change increasingly helps to reduce the hunger in the world until 2080. The best guess and the mean of the triangular distribution function are both in

	Based on Parry et al.		Based on Tubiello et al.	
Warming	**best guess**	**Mean**	**best guess**	**Mean**
0.87 °C	36.3	40.8	0.7	2.6
1.00 °C	37.3	45.3	1.4	5.0
1.75 °C	71.3	94.8	28.0	34.7
2.50 °C	121.6	164.5	80.9	87.6
3.10 °C	165.7	229.9	139.0	146.0
4.00 °C	239.8	345.1	253.3	260.4
5.00 °C	337.5	499.8	419.8	425.6

Table 7.9: Comparison of extrapolating different statistical measures for millions at risk of hunger to higher temperatures; own calculations based on the IPCC Fourth Assessment Report (Easterling et al. 2007: 299) and a triangular probability distribution function as defined in the text above

between these extreme scenarios. But the best guess is closer to the scenario with full CO_2-fertilization, and therefore the shape of the curve and extrapolation to higher numbers is quite different. The effect of choosing either the best guess or the mean is much smaller for the data from Tubiello et al., as was shown in figure 7.3. Here, the shape and direction of the curves with, without and with partial CO_2-fertilization is not fundamentally different. Rather, the results without CO_2-fertilization are somewhat lower over the whole century. Therefore the results based on Parry et al. are more volatile with respect to assumptions regarding CO_2-fertilization and the best guess values drop below those based on Tubiello et al. for higher temperatures. The results based on Tubiello et al. are only slightly different for the best guess and the mean. The numbers are reported in table 7.9.

In light of this large uncertainty of the extrapolation to higher temperatures, it is interesting to look at the projections of hunger due to climate change as given in Fischer et al. (2005: 2080). Here, the highest point estimate is for 830 ppm CO_2. This corresponds to a temperature rise of 4.2°C in PAGE. Thus, from the temperature rise levels in the table above, only the 5°C warming needs to be calculated with help of an extrapolation. This information covering a wider range of temperature rise than the data taken from the IPCC report is used in the following to improve the extrapolation of the previous data to higher temperatures.

For the projections as given in Fischer et al. (2005), the additional number of people at risk of hunger is taken from figure 10 (p. 2080) at intervals of 100 ppm. These CO_2-concentrations are then replaced by the corresponding levels of temperature rise in PAGE. The highest concentration for which the consequences

ppm	Additional millions at risk of hunger	PAGE transient temperature
330	0	–
400	18	0.7
500	40	1.5
600	70	2.4
700	108	3.2
800	155	4.0
830	172	4.2

Table 7.10: People at risk of hunger as given in Fischer et al. (2005: 2080); own calculation of the transient temperature on the basis of the PAGE model

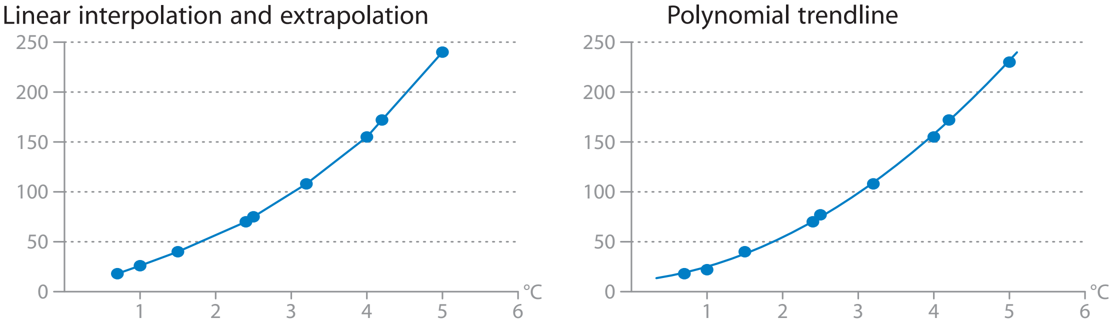

Figure 7.7: The values for a 1°C, 2.5°C, 4°C and 5°C warming are derived through a) inter- and extrapolation, and b) a polynomial trend function; based on data from Fischer et al. (2005)

on hunger are displayed in the original graph is 830 ppm, the lowest 330 ppm. Table 7.10 displays the data.

From these data, figures are derived for a 1°C, 2.5°C, 4°C and 5°C warming to make the numbers comparable to those above. However, it should be kept in mind that the values below 5°C that can be retrieved without extrapolation are more reliable and shall therefore be given more importance in the further work.

Figure 7.7 compares a graph where the values for 2.5°C and 5°C were derived through linear inter- and extrapolation (interpolation between neighbouring values and extrapolation from the highest two values) to a graph where they were calculated with help of a polynomial trend function analogous to the procedure above for the data from the IPCC Fourth Assessment Report.

The curve with the values from the linear interpolation is smoother and looks like the more likely fit. The main difference is for the values at 5°C warming. Here the polynomial extrapolation with a trend line adapted to the existing results leads to a sudden decrease of the curve's gradient that is not in line with the qualitative

Mathematical Form	Result for 5°C	Result for 4.2°C	Result for 4°C
linear (from last two data points)	240	172	155
polynomial with (0/0)	224	172	155
polynomial without (0/0)	229	172	155
Potential	196	172	155
exponential without (0/0)	306	172	155

Table 7.11: Different mathematical methods for extrapolation

evidence about climate change impacts at higher temperatures described above, e.g. evidence from graph 5.2 in Easterling 2007, page 286, reproduced as figure 6.1 on page 128 of this thesis and scrutinized for high temperature slope in chapter 6.2; (cf. Fischer et al. 2005: 2078). The drop in the curve's gradient is even more pronounced for the use of a potential trend line. A polynomial trend line excluding the calibration point (0,0) leads to a slightly smaller decrease of the curves gradient between 4.2 and 5°C compared to the last interval before, but the drop is still there. An exponential trend line on the other hand leads to a very high estimate of over 300 additional millions at risk of hunger for 5°C warming. The estimates for 5°C from different extrapolation methods are summarized in table 7.11. The results which are lower than the linear interpolation are rejected because decelerating climate change impacts with rising temperatures are not in line with the qualitative state of the art. The exponential value on the other hand is very high, and in order to remain on the conservative side the values from the linear extrapolation are reported in the following. This figure is probably rather an underestimate as an increasing slope of the impact curve for higher temperatures is expected. Table 7.12 reproduces the results based on Fischer et al. (2005) as well as the results from the IPCC Fourth Assessment Report data for comparison.

The numbers are higher than the numbers with CO_2-fertilization that were derived from the IPCC Fourth Assessment Report for a small warming of just 1°C, but they rise slower with increasing global temperature levels. For the 4°C warming, the number based on the graph in the 2005 publication is only 67% of the value with CO_2-fertilization based on the IPCC Report as it was derived above. This is interesting because the result for 4°C based on the publication by Fischer et al. (2005) was derived from figure 10 (p. 2080) in the original source with only a transformation to temperature-based results. No inter- or extrapolation was involved for this value. The number for the 5°C warming, on the other hand, is based on a more speculative extrapolation which may have led to too low results.

	Parry et al. (AR4)			Tubiello et al. (AR4)			Fischer et al. 2005
Warming	**with CO_2-fert.**	**best guess**	**no CO_2-fert.**	**with CO_2-fert.**	**best guess**	**no CO_2-fert.**	**Linear interp.**
1.0 °C	20	37	85	−8.9	1.4	23	26
2.5 °C	−15	122	379	60	81	122	75
4.0 °C	−15	240	872	230	253	299	155
5.0 °C	0	337	1311	397	420	460	240

Table 7.12: Additional millions at risk of hunger; own calculations based on data from the IPCC Fourth Assessment Report (Easterling et al. 2007: 299) and Fischer et al. (2005)

The difference to the corresponding numbers for millions at risk of hunger (with full CO_2-fertilization) projected by Tubiello et al. is 40%.

Interpreting this numerical comparison, it is interesting to recall why the best guess numbers based on data from the IPCC Fourth Assessment Report may differ from those given in Fischer et al. (2005), although the IPCC also cites data from the same crop and trade models by Tubiello, Fischer et al. First, only results with CO_2 fertilization are given in Fischer et al. (2005). But these numbers are different even from the results with CO_2-fertilization based on Tubiello et al. and for values derived without extrapolation. Different assumptions on the effects of CO_2-fertilization can therefore not be the only reason for the difference. There is also a slight difference between the two studies regarding the underlying climate models: Fischer et al. (2005) relies on both the HadCM3 and the CSIRO climate projections, whereas the data cited in the IPCC report relies solely on climate data from HadCM3. Another reason for the small difference in the data may be rounding errors, inaccuracies in the transmission from graphical to numerical data and deviations between the trend line given in Fischer et al. (2005: 2080) and the numerical data presented in the IPCC report. For although the single number given in the text by Fischer et al. (2005) is the same as in the IPCC report (almost 120 additional millions at risk of hunger in 2080), the graph in the Journal article by Fischer et al. (2005) does not exactly reflect the data in the IPCC report. For example the IPCC-figure for 2050 (9 additional millions at risk of hunger) is definitely lower than the corresponding point for 532 ppm in the graph in Fischer et al. (2005: figure 10). In the light of the general uncertainties involved, none of the numbers are so far apart that the differences could be considered a serious problem for the integrity of this thesis.

Therefore, the figures for people at risk of hunger in Fischer et al. (2005) are an important hint to the development of a convincing extrapolation function. The number of people at risk of hunger rises slower in the results from Fischer et al. (2005) than in the extrapolated data from the IPCC Report. This suggests that the extrapolation of the data taken from Easterling et al. (2007: 299) may have delivered rather too high estimates for the extrapolation to 4°C and 5°C. However, the results based on Fischer et al. (2005) are rising slower already for lower levels of warming, for which no extrapolation is involved for the data from Easterling et al. either. For 3.1°C warming, Tubiello et al. project with 117 million more people at risk of hunger than Fischer et al. (2005) with 103 million. For lower levels of temperature rise the opposite was the case. The difference at 3.1°C is less pronounced than for the high warming numbers which are based on extrapolation assumptions for the IPCC data.

In face of the huge uncertainties it may be argued that a disparity of 40% of the result is not too important. The aim of the assessment of millions at risk of hunger due to climate change is to get an idea of the likely order of magnitude, not to derive exact results. Furthermore, even without considering the missing certainty about CO_2-fertilization, the results from Fischer et al. (2005) are likely to be an underestimate as weather extremes were not regarded in the modelling process (Fischer et al. 2005: 2071f).

The results based on Parry et al. are persistently higher than those based on data from Fischer et al. (2005), but for the best guess they are lower at 4°C and 5°C warming than the numbers derived from Tubiello et al.

In the following, the insight from the numbers based on Fischer et al. is used to improve the extrapolation of the curves based on data from the IPCC Fourth Assessment Report to higher temperatures. The results above lead to the conclusion that the polynomial trend functions for the curves based on IPCC data may be too steep. Therefore, as an alternative for the extrapolation of the curves based on IPCC data, linear extrapolations were tested. The values for 1°C and 2.5°C were maintained from the polynomial trend line. Linear extrapolations were used for 4°C and 5°C, best guess values.

In a first linear extrapolation the figures for 2050 and 2080 were taken as the calibration for the linear trend, that is the values for a 1.75°C and a 3.1°C warming. As a second alternative, the basis for the calibration of a second linear extrapolation were the impact numbers for 3.1°C and for 2.5°C, the latter derived with the polynomial function above. Figure 7.8 illustrates these extrapolation methods.

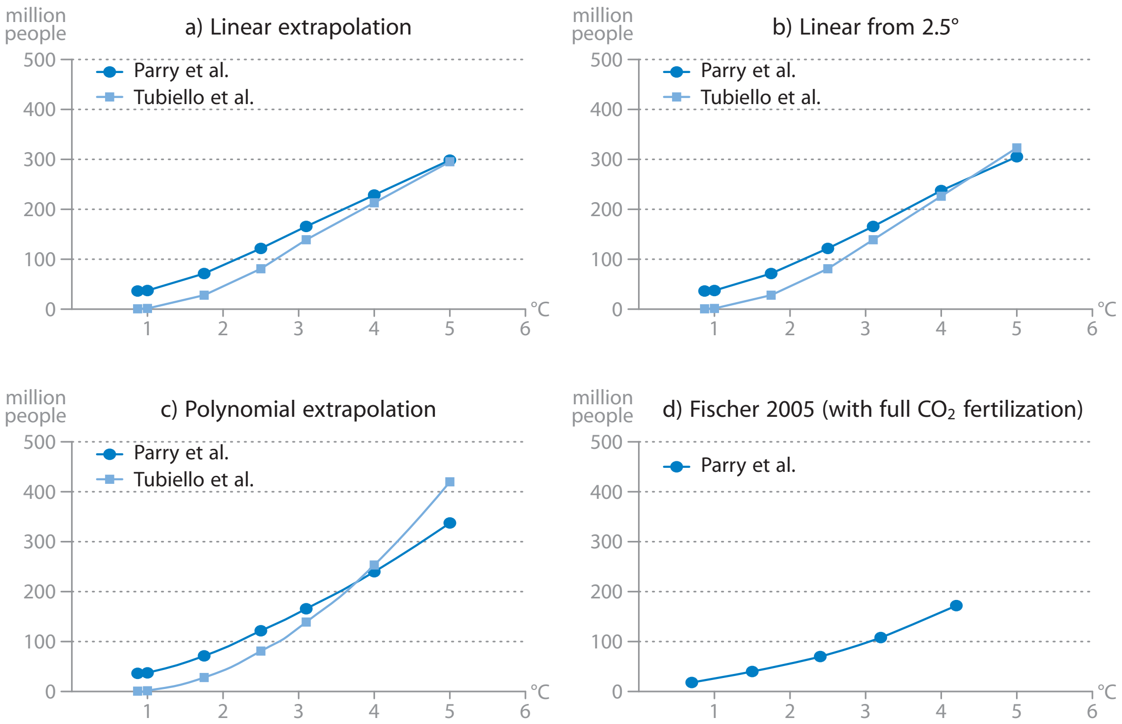

Figure 7.8: Different extrapolation methods for the best guess values of millions at risk of hunger based on data from the IPCC Fourth Assessment Report (Easterling et al. 2007: 299); a) linear extrapolation calibrated to the results for 1.75°C and 3.1°C warming; b) linear extrapolation calibrated to the results for 2.5°C and 3.1°C warming; c) polynomial extrapolation; d) results based on data from Fischer et al. (2005: 2080) for comparison of the slope, contrary to the other results with full CO_2-fertilization; in all graphs the impact is given in millions at risk of hunger and the temperature rise (x-axis) in °C.

No clear preference for either of the two linear extrapolation methods recommends itself from the graphs. However, they show a visible difference insofar as in graph b) the results based on Tubiello et al. surpass those based on Parry et al. for 5°C warming. This is not the case in graph a). From an analytical point of view, the method presented in graph b) has an advantage, because the slope of the curve doesn't decrease for the last two intervals compared to the previous one, a feature of graph a) which is not in line with general expectations on climate change impacts in the agricultural sector (Easterling et al. 2007: 275). Therefore the linear extrapolation from graph b) is used in the following, that is an extrapolation from the values for 2.5°C warming and 3.1°C warming.

In table 7.13 the results from Tubiello et al. with full CO_2-fertilization for both linear and polynomial extrapolation are compared to the results based on the data taken from Fischer et al. (2005). As full CO_2-fertilization is assumed in Fischer et al. (2005), the data from Tubiello are equally reported with full CO_2-fertilization, although this is not regarded as the most likely result. Tubiello et al. is chosen as

	Tubiello et al. (AR4)		Fischer et al. 2005
Warming	**Polynomial**	**Linear**	**Linear**
1 °C	−9	−9	27
2.5 °C	60	60	76
3.1 °C	117	117	103
4.0 °C	229	202	153
5.0 °C	397	296	238

Table 7.13: Comparison of polynomial and linear extrapolation results for millions at risk of hunger from Tubiello et al. and Fischer et al. 2005, both with CO_2-fertilization

they use the same model as Fischer et al. (2005) and results should therefore be comparable.

In the linear extrapolation, the results based on data from the IPCC report (AR4) are still higher. But this is to be expected for a sensible extrapolation, as they are already higher for the 3.1°C warming. For this level of warming, no extrapolation was necessary for the data from all different sources.

It may be argued that the interpolation for deriving the values at 1°C and 2.5°C warming should also be linear for the sake of consistency. However, the distinctly better fit of a polynomial trend line to the four calibration points based on data from AR4 suggests that the relationship is indeed not a linear one for lower levels of temperature rise. The assumption that a linear extrapolation for higher temperatures is the better fit is also based on the insight from one graph only (Fischer et al. 2005: figure 10), which may be wrong. Therefore the polynomial interpolation for lower levels of temperature rise is maintained. The choice for the linear extrapolation to higher temperatures reflects the attempt to present conservative values for 4°C and 5°C warming.

7.1.8 Defining a probability distribution function

All values of the triangular probability distribution function are derived as the average of the values based on the data in the IPCC Report: the lower bound values from results with full CO_2-fertilization, the mode from the best guess values and the upper bound from data without CO_2-fertilization. The data from Fischer et al. (2005) are not included here because the data from the model is also part of the information presented in the IPCC Report. An average of all three numbers would be like double-counting the AEZ model. Numbers are derived with linear extrapolation to 4°C and 5°C. Table 7.14 summarizes the numbers.

Warming	Lower bound	Mode	Upper bound
1.0 °C	5	19	54
2.5 °C	23	101	250
4.0 °C	93	229	541
5.0 °C	148	314	735

Table 7.14: Millions at risk of hunger; values defining a probability distribution function for further use in PAGE; own calculations based on Easterling et al. (2007: 299); Fischer et al. (2005: 2080)

The upper bound to uncertainty may appear rather high. It is not considered likely that no CO_2-fertilization at all will take place. On the other hand, the uncertainty range above is based on the results of three different sources only. Two of these are from the same model. This is a strong indication, that true uncertainty has been underestimated, as a wider range of studies would likely lead to a wider range of results. Furthermore sea-level rise, flooding, extreme weather events, and pests or problematic soil conditions have not been sufficiently integrated in the studies (Fischer et al. 2005: 2072; Parry et al. 2004: 57; Lotze-Campen 2009).

7.2 Valuation of hunger

The welfare valuation of hunger is extremely difficult. In PAGE, all impacts are measured with the unit '\$' or '% of GDP'. That is, welfare changes in PAGE are always measured in terms of money. This is the prevailing approach in cost-benefit analysis of climate change. If costs and benefits are to be compared directly, they need to be in the same unit. Therefore, only one unit is usually used in cost-benefit analysis of climate change. And the unit that is often used for a wide range of impacts is money.

But no monetisation approach exists for the suffering caused by hunger. A lot of studies exist on the value of a statistical life. For the people dying of hunger these findings might be used. However, the monetisation of the loss of human lives is very controversial. Many stakeholders argue that it is not meaningful at all. Figure 7.9 shows the results of a survey, in which stakeholders in Europe were asked for their opinion on the suitability of monetisation of various possible impacts of climate change, and the phenomenon of global warming as a whole.

Table 7.15 summarizes the structure of the respondents to the survey according to their professional background or stakeholder category. They play a major role in the political debate about climate change. Thus, for the issue of climate change,

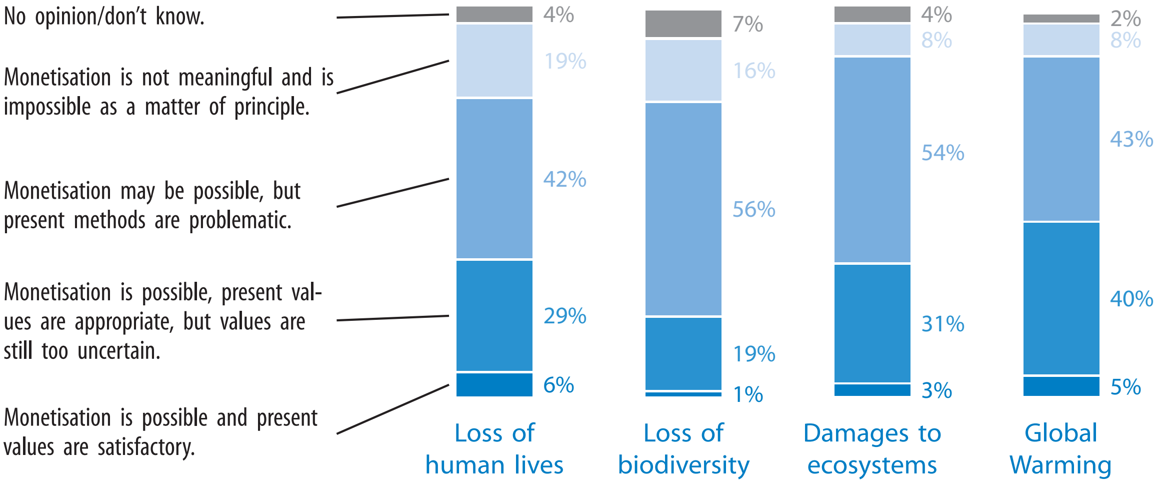

Figure 7.9: Survey results on the suitability of monetisation of different impacts (Faberi and Gaggi 2007: 9)

Group	Respondents	Percentage
Researchers	47	24 %
Energy Supply	30	15 %
Governmental Energy & Environmental Agencies	25	13 %
Consultants	24	12 %
Other, please specify	21	11 %
NGOs	13	7 %
Associations	14	7 %
Energy Demand	12	6 %
Regulators / Authorities	9	5 %
Politicians	5	3 %
Total Respondents	200	100 %

Table 7.15: Structure of the respondents to the survey on the suitability of monetisation (Faberi and Gaggi 2007: 6)

the mix of respondents may be taken as a suitable approximation to the group of problem owners as defined in decision analysis.

One fifth of the survey respondents think that the monetisation of the loss of human lives is impossible as a matter of principle. Another two fifths say that the present methods for the monetisation of the value of human lives are problematic. Only 6% find present methods and values satisfactory. Another 30% agree with the basic methodology available, but find that values are still too uncertain.

7.2.1 Compendium of results

On the whole, the results of this survey cast serious doubts on the suitability of valuing the welfare losses caused by hunger in dollars, especially in a model based on decision analysis. In a model based on decision analysis, the model users should be free to decide how to deal with this question. While only the results from the survey above and the judgement from the author are available, the best form for presenting the results is with two different metrics: market losses in dollars and hunger measured in additional million undernourished people due to climate change. In tables 7.16 and 7.17, these results are presented.

From the numbers for millions at risk of hunger, figures for people actually dying from hunger are estimated based on current data on the proportion of hungry people dying from the consequences of hunger every year, that is 3.8% (Ziegler 2009). As the numbers for people dying from hunger are directly derived from the results for millions at risk of hunger above, they should not be counted as a third, different metric for the presentation of impacts. Rather, a piece of information already contained in the number of people at risk of hunger is presented specifically. Results for annual impacts are displayed in table 7.18.

	Market impacts (% of gross agricultural product)		
Warming	**Mean**	**90 %-confidence interval**	
1.0 °C	6 %	2 %	10 %
2.5 °C	−5 %	−13 %	2 %
3.6 °C	−15 %	−23 %	−6 %
4.0 °C	−19 %	−27 %	−11 %
4.4 °C	−23 %	−32 %	−15 %
5.0 °C	−30 %	−40 %	−21 %

Table 7.16: Market impacts of climate change in the agricultural sector; positive values are gains and negative values are costs of climate change

	Additional people at risk of hunger (millions)			
Warming	**With CO_2-fertilization**	**Mode**	**Without CO_2-fertilization**	**Mean**
1.0 °C	5	19	54	26
2.5 °C	23	101	250	125
4.0 °C	93	229	541	288
5.0 °C	148	314	735	399

Table 7.17: Additional millions at risk of hunger due to climate change: a triangular probability distribution function

	Additional people dying from hunger (millions/a)			
Warming	**With CO_2-fertilization**	**Mode**	**Without CO_2-fertilization**	**Mean**
1.0 °C	0.2	0.7	2.0	1.0
2.5 °C	0.9	3.8	9.5	4.7
4.0 °C	3.5	8.7	20.6	10.9
5.0 °C	5.6	11.9	28.9	15.2

Table 7.18: People expected to die from hunger due to climate change: a triangular probability distribution function

This presentation of the expected impacts of climate change on the agricultural sector is by far the most meaningful. It is easy to understand and shows the most important dimensions of the impacts. Still, it is aggregated enough to grasp the whole extent of the impacts presented all at once. This form of presenting the results is explicitly recommended here as the most suitable approach. It is likely that other impacts than those above will exist even in the agricultural sector. Their omission here is due to lack of knowledge about them, not to the chosen form of the presentation of results. It is recommended to point out this possible omission of impacts together with the presentation of results.

A further aggregation of impacts into just one metric rather obscures than further clarifies the results. In the process of aggregating the sufferings of hunger and monetary losses, valuable information about the kind of impact is lost for gaining just the advantage of reducing the number of impact metrics from two to one. Any political decision maker should be capable of assimilating information that is presented in two metrics. And the two metrics monetary costs and risk of human lives lost are likely to be among the most important factors in other impact sectors as well. Therefore, this distinction remains sensible even when the impact assessment is broadened to other sectors.

What any sensible person can accomplish is more difficult in a cost-benefit model. Where the costs of mitigation are presented in monetary terms only, whereas the benefits of mitigation are given in avoided monetary losses and avoided deaths, the loss of human lives tends to be forgotten. The simple optimization approach of cost-benefit models is only possible for one metric. When monetary costs and benefits of mitigation are compared in such a model, the result is that the losses of lives are often not taken into account at all. They are then implicitly valued at zero costs, which is definitely wrong.

35% of the respondents to the questionnaire above voiced the opinion that meaningful methodologies exist for the monetisation of the loss of human lives, even if most of them agree that the current values are too uncertain. Nevertheless, these people might wish to explore what the aggregation of all impacts into a monetary metric would mean for the cost-benefit analysis of climate change in PAGE. Emphasizing that such an aggregation is not necessary for the presentation of impacts and ethically difficult, such an exploration of the consequences of including both types of impacts into one monetary model is made in the following.

7.2.2 Value of a statistical life – methodologies

There are no surveys for the monetary valuation of suffering caused by hunger, but a rather broad literature exists on the value of a statistical life. Therefore, as a first approximation to the valuation of hunger, a context-specific measure for the value of a statistical life is multiplied by the additional number of expected deaths from the consequences of hunger due to climate change.

It is important to note that these surveys do not try to measure the value of human life, but rather the treatment of risk in societies. This paragraph deals with the value of a statistical life, not the value of any specific human life which would be even more difficult to measure in monetary terms. If in the following the term 'statistical life' or 'statistical death' is used, this is meant to deal with the risk of death in a large group of people that is so high, that on average it is expected that one person will die due to this risk. For example, in Germany every year between 4000 and 5000 people die in traffic accidents (Statistisches Bundesamt Deutschland 2008). It can thus be said that the German society seems to value the conveniences and pleasure of driving higher than 4000 statistical lives. This does not mean, that the German public finds any one death of a specific person acceptable and would not do a lot more to try and save that person, if they could. It is entirely a measure of risk that is statistically distributed over a large population. Nor does it mean, that no measures are taken to reduce the number of fatal traffic accidents. But nevertheless the Germans still use cars frequently, although the number of people dying in car accidents has been above 4000 for many, many years.

All societies are confronted with the risk of accidental deaths. The question how much money people or societies as a whole are willing to spend to reduce the risk of death by a certain percentage is not an abstract scientific construct, but rather an everyday decision. However, people usually do not take these decisions consciously of the exact risk involved and never take them free from the context of other costs and benefits that are connected to the decision. The risk of death is a very small one in most of the decisions made, and people do not know the numerical probabilities of the risks they take. It is therefore very difficult to derive an estimate of the value of a statistical life from people's actions and statements. Five approaches exist in the literature:

- Human capital approach
- Avertive behaviour approach
- Compensating wage approach
- Contingent valuation
- Upper sensible limit to the value of a statistical life due to the GDP-rebound effect

The human capital approach: The human capital approach is rather outdated and not normally used any more today. It was based on the assumption that the value of a statistical life to society could be connected to the contribution of that person to GDP, that is the income and/or expenditures of a person or related measures. Today, a consensus is emerging at least in democratic countries that the value of a statistical life should be based on individual preferences rather than human capital. (European Commission 1999: 85)

Avertive behaviour approach: In the avertive behaviour approach, it is assumed that people and societies deliberately spend money to reduce the risk of fatal accidents, and that these activities are pursued to the point where their marginal costs equal the marginal value of reduced risk of death (Friedrich et al. 2004: III-8). Examples are smoke detectors or seat belts. From the percentage of people who make the expenditure, the price of the risk reducing device and the reduction in the probability of a fatal accident, a value of a statistical life is derived. One problem of the approach is that it is impossible to know, how much people would at the most be willing to pay. Those who buy a smoke detector may or may not be willing to pay double the price for it, if it weren't available at a cheaper rate. Those who do not buy the smoke detector might or might not buy one, if the prices were just half the current amount – or two thirds, one third or any other quantity. Therefore the percentage of people who do buy the device is the only way to deduce the real utility of the device to society.

Furthermore, most people do not make the decision whether to buy a smoke detector on the basis of a risk-cost analysis. Probably most people can not quantify the reduction in risk they get from a smoke detector or other safety device. Many of those who do not buy them, probably do not know the price of the device either. So if they do not decide to buy a smoke detector, this is hardly a monetary decision.

Other factors like life-style, the promotion for the safety device, culture and the behaviour of family and friends may be a lot more important. Finally, a safety device may have positive side effects: mostly not only fatal accidents are reduced but also injuries and sometimes damage to property. Some studies try to account for these side effects.

Evidence suggests that the avertive behaviour approach leads to rather low values for a statistical life. Friedrich et al. found average values of 1–1.5 million € (Friedrich et al. 2004: III-9).

Compensating wage approach: Some employments like for example on oil platforms are riskier than other employments. In the compensating wage approach it is assumed that the employees will only take these riskier jobs, if the higher risk of a fatal accident is reimbursed through higher wages. From the difference in wages and the difference in risk, a value for a statistical life is deduced. Other differing characteristics like workplace comfort and social prestige need to be accounted for in the assessments to avoid distortions.

Again, it is hardly likely that workers can quantify the risk they accept, and the labour market may not be as open and competitive as the compensating wage approach suggests. Furthermore, it may not be possible to account for all correlated characteristics that influence the choice of employment besides the risk of fatal injury. But at least the choice of a workplace may be a decision which many people consider carefully.

A broad range of studies relying on the compensating wage approach exists. The range of values produced by these studies is large, more than an order of magnitude. Friedrich et al. give 5 million € as a conservative mean value for a statistical life from the lower end of the range. (Friedrich et al. 2004: III-7f)

Contingent valuation: While the avertive behaviour and the compensating wage approaches try to deduce the implicit value that people give to the avoidance of risk from their behaviour in real-life situations, the contingent valuation approach asks directly for the valuation that people give to the good like risk reduction. Hypothetical markets are constructed for this purpose, and the questions are constructed in a way to derive the marginal value of the good in question. The advantage of this method is, that it can be used even for goods for which no markets exist. The difficulty is to make the hypothetical market description realistic enough to derive real valuations from the respondents. A test to the success of this endeavour is, whether the answers vary systematically with socio-economic characteristics of the respondents and are not random. Biases may still exist, however. For example the lack of a real budget constraint may induce people to state a higher willingness to pay than they would show in real life. Furthermore, the stated willingness to pay is often not as sensitive as expected to the variation of risk. It may be that people do not intellectually capture the meaning of very small risks (cf. Friedrich et al. 2004: II-9ff). But it may also be that their risk aversion is not linear with the size of the risk.

A study by Jones-Lee based on contingent valuation derived a base value of 4 million € for a statistical life in the context of motor vehicle accidents (Jones-Lee 1989; cited after Friedrich et al. 2004: III-12). A more recent study in the framework of ExternE derived a value of 1 million € (Bickel and Friedrich 2005: 146). Here, the hypothetical market consisted of some medicine that reduces the risk of a deadly disease by a certain percentage.

Upper sensible limit to the value of a statistical life due to the GDP-rebound effect: Some authors argue that an upper limit to a sensible value of a statistical life can be derived from the relationship between GDP per capita and life expectancy. This argument relies on the observation that the life expectancy is higher in richer countries, and within countries the richer tend to live longer. According to the proponents of the argument it would therefore be irrational for decision makers to invest so much money in risk reducing activities, that more people would die due to the reduced per capita wealth than deaths could have been prevented by the expensive measures. For the US, a study from the early 1990s derived $5–12 million as an upper limit to the value of a statistical life. (Desaigues et al. 2006: 28)

However, the relationship between GDP per capita and life expectancy is not necessarily fixed. It may change over time or from country to country, but it may also be actively influenced by politics. The value cited above can therefore hardly be taken as an absolute upper limit to sensible expenditures to reduce the risk of human deaths.

7.2.3 Value of a statistical life – equity considerations

The risk aversion of people and the implicit valuation of a statistical life depend on many factors. Results differ for example depending on whether the risk is voluntarily accepted or forced on the person in question. A UK government guideline recommends to double the value for a statistical life whenever the risk is involuntary (Friedrich et al. 2004: III-46). The context may also be important. The ExternE team suggest to differentiate between deaths from road accidents and deaths from air pollution, as the latter affects predominantly older people (Bickel and Friedrich

2005: 138). It is an ethical decision whether these recommendations are accepted. They are not included in the calculations of this thesis.

Another important factor is the country where the study was carried out. Naturally, the ability to pay for risk reductions is higher in richer countries, and correspondingly the willingness to pay is higher as well. This is ethically difficult, because the data suggests that a human life in Europe is worth more than a human life in Bangladesh. This is not in line with the basic ethical judgement of many people, but the point is of crucial importance for a problem like climate change with global impacts and drivers which are unevenly distributed around the world. In the following, it is assumed that the problem owners using this model do not agree with the supposition of different values for statistical lives of poor and rich people. One justification for this bold assumption can be taken from the Universal Declaration of Human Rights, adopted by the United Nations in 1948, which describes a wide international agreement in the political arena. The first three articles of the Declaration are:

> Article 1. All human beings are born free and equal in dignity and rights. They are endowed with reason and conscience and should act towards one another in a spirit of brotherhood.
>
> Article 2. Everyone is entitled to all the rights and freedoms set forth in this Declaration, without distinction of any kind, such as race, colour, sex, language, religion, political or other opinion, national or social origin, property, birth or other status. Furthermore, no distinction shall be made on the basis of the political, jurisdictional or international status of the country or territory to which a person belongs, whether it be independent, trust, non-self-governing or under any other limitation of sovereignty.
>
> Article 3. Everyone has the right to life, liberty and security of person.

The equal dignity and entitlement of all humans to the rights set forth in the Declaration is strongly emphasised. The equal right to life and security of person is even specifically guaranteed. And property is explicitly ruled out as a possible reason to value the basic human rights differently for different people. This is incompatible with any assumption other than that the value of a statistical life must be counted equally for people all over the globe in the model. In accordance with the guidelines of decision analysis, this understanding is presumed as the basis for the assessment below, reflecting a strong consensus of decision makers around the globe.

It must, however, be noted that this ethically founded assumption can not be directly derived from the principle of willingness to pay as a measurement for value, which is frequently employed in economics. Political valuation is thus considered more important than the simulation of markets or deduced information from similar existing markets. This is an ethical decision, which no science can objectively resolve for decision makers.

There are two basic possibilities to deal with this issue. Some scientists (e.g. European Commission 1999: paragraph 6.3.2) suggest to derive the values for a statistical life locally or regionally according to the willingness to pay or the willingness to accept compensation, and then apply equity weighting in the aggregation process. Through equity weighting, the willingness to pay from poor regions would count more and thus the divergent abilities to pay for safety would be (partially) approximated to more similar values around the globe. However, this method is impossible to apply here, as surveys on the value of a statistical life are not available for all world regions. Only a very limited number of studies from countries with a low per capita income exist, which are displayed further down. Still, the principle can be used to help bridge the gap between the political decision to value human lives equally around the world and the method of willingness to pay as a common economic basis for valuation.

In the following, a single global number and information about a probability distribution function for the global value of a statistical life is derived from the literature. The number is then used globally for the purpose of assessing climate change impacts. This way it is safeguarded that a statistical human life is counted equally around the globe. Of course these results may then not enter the procedure of further equity weighting in the PAGE model. Such an equity function is currently integrated into an expanded version of the PAGE model. But this part of PAGE was not used for the Stern review, where equity weighting was not included numerically. Stern et al. suggest that an increase in impact figures of roughly 40% might be adequate to correct for the lack of equity weighting (Stern 2007: 163).

7.2.4 Value of a statistical life – survey results

Many studies on the value of a statistical life exist, mainly from Western industrialised countries. Table 7.19 summarizes a wide range of these results.

Source	Recommended range (million €)	Recommended value (million €)
ExternE earlier	1.0 – 5.0	3.0
ExternE CV 2004 (UK, I, F) (1)	–	1.0
Giergiczny, Poland (wage)	0.8 – 2.4	–
CSERGE 1999 meta-analysis (wage)	2.9 – 100	6.5
Wage (6 studies, UK+Austria)	4.0 – 74.0	–
Avertive behaviour (3 studies)	1.0 – 1.5	–
EC guideline	0.65 – 3.5	1.4
UK gov. Guideline	–	1.2 (involuntary 2.4)
US labor market data (Viscusi)	5.0 – 12.0	7.0
US product markets (Viscusi)	0.8 – 10	–
Sweden medical intervention mean cost per life saved (2)	–	25 (3.8)
Non-US labor market (Viscusi) (3)	0.2 – 69 (0.7–20)	–

Table 7.19: Estimates of the value of a statistical life from a range of studies; CV = contingent valuation, wage = compensating wage approach; (1) survey participants were asked for their willingness to pay for a new product against disease, the value above was derived from the assumption that the risk avoided is 5/1000, the same question for a 1/1000 risk avoided leads to a values of a statistical life of 3.3 million; (2) the lower number is without outlier result; (3) Australia, Austria, Canada, Japan, UK, Hong Kong, India, South Korea, Taiwan, Switzerland, in brackets without outliers. Results from Friedrich et al. (2004), Viscusi and Aldy (2003), Giergiczny (2008), European Commission (1999).

In the contingent valuation study from ExternE (Friedrich et al. 2004) not only a recommended value is given, but also a probability distribution function describing the distribution of answers from the various participants. They state that a Weibull distribution with median 1.1 million € and mean 2.3 million € is the best fit to their data (Friedrich et al. 2004: III-34). Figure 7.10 shows such a probability distribution function.

Most of the probability is concentrated to the left of the graph, with a very long tail towards the right. The authors suggest the median (1.1 million €) as a conservative recommended value for further use, not the higher mean (2.3 million €). In the following, sensitivity analysis with two different figures for the value of a statistical life is done rather than to employ a probability distribution function. This better reflects the ethical choice that decision makers have to make themselves. Probability distribution functions in decision analysis models should be used for uncertainty, not ethical choice. Still, the information on the distribution of opinions about the value of a statistical life is interesting. The values themselves may be too

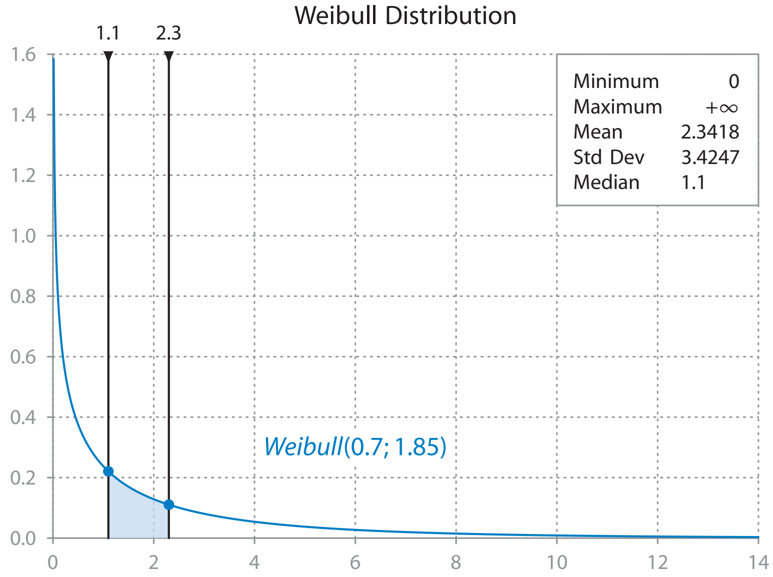

Figure 7.10: Probability distribution function for the value of a statistical life (Friedrich et al. 2004: III-34)

high, as the study gives results for Italy, UK and France only. This is not a likely match for a global value of a statistical life. In the following section, the knowledge on benefit transfer in the context of the value of a statistical life is analysed.

7.2.5 Value of a statistical life – benefit transfer

It was found that the willingness to pay for a higher life expectancy rises faster with income in low-income countries. This result is based on a comparison of estimates in European countries (Desaigues et al. 2006: 24). Viscusi and Aldy found an income elasticity η of 0.5 to 0.6 in a meta-analysis of the value of a statistical life (Viscusi and Aldy 2003: 6). Desaigues et al. came to the conclusion that an income elasticity of 1 performed better than a lower value (Desaigues et al. 2006: 22). A range in between these two results was found in a study about the income elasticity of the value of an injury: it was estimated to be between 0.6 and 1 (Viscusi and Evans 1990: 372). The data base for these values includes studies from many countries, with a clear majority from high and middle income countries.

From the results above, the study by Giergiczny with a VSL of 0.8–2.4 million € (Giergiczny 2008: 220) is interesting for the derivation of a global value, because the Polish per capita income in the year of the study publication was just 25% above the global average per capita income (World Bank 2008). The estimate can therefore be assumed to be of the right order of magnitude for a global value of a

Country	Value of a statistical life (million US$$_{2000}$)	GNI per capita (US$)
Taiwan A	0.2 – 0.9	17930
South Korea	0.8	19700
Hong Kong	1.7	31600
Taiwan B	0.7	17930
India A	4.1	950
India B	1.0 – 1.4	950

Table 7.20: Estimates from different studies for the value of a statistical life derived with the compensating wage approach in non-Western countries (Viscusi and Aldy 2003: 27f)

statistical life. And it is not an outlier result, but fits into the range of studies on the value of a statistical life. In table 7.20 some more results from non-Western countries are presented. They all belong to the category 'developing countries' under the UNFCCC (United Nations Framework Convention on Climate Change), but the per capita incomes in Taiwan, South Korea and Hong Kong would suggest a different classification. Only in India, the GNI per capita is clearly below the world average of 8000 US$/capita in 2007. The GNI values are also reported in the table. The estimates for the value of a statistical life were derived with the compensating wage approach.

When the recommended range from Giergiczny is converted to US$ and adapted to the world average per capita income with an income elasticity of 1, the result is US$ 0.8–2.5 million. For an income elasticity of 0.6 the value would be US$ 0.9 to 2.7. The difference is small in face of the other uncertainties. In line with these findings and the data above, a value of US$ 1 million is used in the following as a rather low and conservative estimate. Sensitivity analysis for other values is easy to do, problem owners can thus use their own values without difficulties. Results for a value of a statistical life of $ 2 million are given as an example.

7.2.6 Discounting impacts from hunger

The income dependency of the value of a statistical life has another important repercussion on the PAGE model. In general, all costs and benefits are discounted in PAGE, according to the theory of cost-benefit analysis. In the Stern Review, the discount rate is split up into the pure rate of time preference and the part of the discount rate accounting for economic wealth (prescriptive approach). The pure rate of time preference is assumed to be very low in the context of an intergenerational optimization (Stern 2007: 31f). The part of the discount rate accounting for economic growth is usually calculated by a multiplication of the per capita economic growth rate with the negative of the elasticity of the marginal utility of consumption η . This discounting is based on the empirical evidence that the same amount of money is worth more to a poor person than a rich person.

If the results for the value of a statistical life increase with future wealth and the discounted impact per unit lost decreases with future wealth due to discounting, than the estimate practically does not change much. If the η from the discounting (negative of the elasticity of the marginal utility of consumption) and the η from the context of the value of a statistical life (income elasticity) are the same, then the effects of both cancel each other out. Practically, this implies that no discounting based on the argument of economic growth is needed for the loss of human lives. (cf. Rabl 1996: 143; Viscusi and Evans 1990: 369)

This is equally the consequence from the Universal Declaration of Human Rights: if every human life is equally important, future deaths can hardly count less on the basis of future people being assumed to be richer. But it is comforting to see that the discounting theory arrives at exactly the same result, when it is thoroughly applied. This is already the general procedure in PAGE, where damages are given as a percentage of GDP. That is, future damages are higher if economic growth leads to higher GDP, but the damages are discounted on grounds of rising per capita income.

A positive pure rate of time preference applied to time scales of several generations is also difficult to reconcile with the equality-principle from the declaration of human rights. Where the time preference does not indicate the desire of an individual to get a good rather sooner than later, but ascribes a higher value per se to earlier generations, the principle of equality is violated.

In the Stern review, a rate of pure time preference of 0.1% is employed, accepting only the small probability of future generations being extinct as a basis for employing a rate of pure time preference. In PAGE2002, a pure rate of time preference between 1% and 3% per year is the standard setting, but any model user can choose their own values.

7.2.7 Valuation of non-mortal hunger

The assessment above of possible values for a statistical life can be applied to try and measure the monetarized costs of death caused by hunger. About 3.8% of undernourished people currently die every year from the consequences of hunger, but it can hardly be said that for the remaining 96.2% of hungry people the lack of food does not imply a serious problem.

The FAO tried to estimate the economic costs of hunger. They produce a figure of $ 30 billion per year for the direct costs of malnutrition (FAO 2004: 11). In their calculation, this includes only costs for medical treatments that would not have been necessary in the absence of hunger. On average, this result implies costs of $ 35 per person undernourished. This figure is extremely low compared to the suffering and reduction in quality of life caused by hunger. Thus it becomes clear that the costs of additional medication are only a very minor contribution to the overall costs of hunger. The FAO equally states, that the indirect costs are expected to be a lot more important than the direct costs. But in absence of a good data basis, they do not produce an exact number for this category. They give 'hundreds of billions of dollars' as a landmark for the magnitude of these costs (FAO 2004: 11). This corresponds to a range of $ 240–1,000 per person undernourished. But even in this wider definition of the costs of hunger, the suffering of the people is not included. Only losses in economic productivity and income, absenteeism and lower educational opportunities were considered. Thus, whereas these numbers are an interesting input to the discussion, they are only a small part of the overall costs of hunger.

No other studies were found that try to monetarize the value of not being undernourished, or that try to compare the value of avoiding hunger to the value of avoiding a statistical death. Furthermore, undernourished people suffer from very different intensities of lack of food. For the numbers of millions at risk of hunger, no information is available as to the intensity of hunger either.

In the following, only a very crude attempt can be made at valuing non-fatal hunger. If no value were set in face of this pervasive uncertainty, this would equal the assumption that non-fatal hunger has no negative value at all, because the phenomenon would disappear from all further calculations. According to the FAO figures above, $ 240–1,000 per person is only a small part of the overall costs of hunger. As an arbitrary, but maybe not completely absurd estimate, the costs of non-fatal hunger are set at 2% of the value of a statistical life. For the assumption of a value of a statistical life of $ 1 million, this would correspond to $ 20,000 per person undernourished. It must be stressed that this assumption is highly subjective. Therefore, the following monetarized results are always given both with and without these costs of non-fatal hunger to isolate the very unreliable numbers for the costs of non-fatal suffering from the monetary valuation of additional deaths derived above. Furthermore, it is easy to adapt the results to any other assumption of the costs of non-fatal hunger, as the final cost estimate is a linear function of this input parameter.

7.2.8 Compendium of monetarized results

The following tables display the monetarized costs of hunger caused by climate change as described above. The mean is here the mean of the triangular distribution function defined by the other three values in the table. The market costs and millions at risk of hunger are displayed again for comparison. Results are for annual impacts.

	Additional people at risk of hunger (millions)			
Warming	**With CO_2-fertilization**	**Mode**	**Without CO_2-fertilization**	**Mean**
1.0 °C	5	19	54	26
2.5 °C	23	101	250	125
4.0 °C	93	229	541	288
5.0 °C	148	314	735	399

Table 7.21: Additional millions at risk of hunger due to climate change

	Additional people dying from hunger (millions)			
Warming	**With CO_2-fertilization**	**Mode**	**Without CO_2-fertilization**	**Mean**
1.0 °C	0.2	0.7	2.0	1.0
2.5 °C	0.9	3.8	9.5	4.7
4.0 °C	3.5	8.7	20.6	10.9
5.0 °C	5.6	11.9	28.9	15.2

Table 7.22: Millions expected to die from hunger due to climate change

VSL = 1 m US$	Costs of additional deaths due to hunger (billion US$)			
Warming	**With CO_2-fertilization**	**Mode**	**Without CO_2-fertilization**	**Mean**
1.0 °C	205	735	2046	996
2.5 °C	872	3848	9507	4742
4.0 °C	3534	8700	20556	10930
5.0 °C	5624	11935	27922	15160

Table 7.23: Monetarized impacts of additional deaths due to hunger caused by climate change employing US$ 1 million as the value of a statistical life

VSL = 1 m US$	Sum of costs of additional hunger (billion US$)			
Warming	**With CO_2-fertilization**	**Mode**	**Without CO_2-fertilization**	**Mean**
1.0 °C	313	1122	3123	1520
2.5 °C	1331	5873	14511	7238
4.0 °C	5394	13279	31375	16683
5.0 °C	8584	18217	42618	23140

Table 7.24: Monetarized impacts of additional deaths due to hunger caused by climate change and the monetarized costs of non-fatal hunger caused by climate change employing US$ 1 million as the value of a statistical life

VSL = 2 m US$	Costs of additional deaths due to hunger (billion US$)			
Warming	**With CO_2-fertilization**	**Mode**	**Without CO_2-fertilization**	**Mean**
1.0 °C	411	1471	4092	1991
2.5 °C	1744	7695	19015	9485
4.0 °C	7068	17400	41113	21860
5.0 °C	11248	23870	55845	30321

Table 7.25: Monetarized impacts of additional deaths due to hunger caused by climate change employing US$ 2 million as the value of a statistical life

VSL = 2 m US$	Sum of costs of additional hunger (billion US$)			
Warming	**With CO_2-fertilization**	**Mode**	**Without CO_2-fertilization**	**Mean**
1.0 °C	821	2941	8185	3982
2.5 °C	3488	15390	38030	18969
4.0 °C	14136	34800	82225	43721
5.0 °C	22496	47741	111689	60642

Table 7.26: Monetarized impacts of additional deaths due to hunger caused by climate change and the monetarized costs of non-fatal hunger caused by climate change employing US$ 2 million as the value of a statistical life

	Market impacts (% of gross agricultural product)		
Warming	**5th percentile**	**95th percentile**	**Mean**
1.0 °C	−2.3 %	−9.6 %	−6.1 %
2.5 °C	12.7 %	−1.5 %	5.4 %
4.0 °C	27.5 %	10.9 %	18.9 %
5.0 °C	39.9 %	20.7 %	30.0 %

Table 7.27: Market impacts of climate change in the agricultural sector; for better comparison negative values are gains and positive values are costs of climate change

VSL = 1 m US$	Mean (billion US$$_{2000}$)	
Warming	**Market impacts**	**Death impacts**
1.0	−159	996
2.5	140	4742
4.0	494	10930
5.0	782	15160

Table 7.28: Comparison of annual market impacts and monetarized annual costs of additional deaths due to hunger caused by climate change for a value of a statistical life of US$ 1 million (year 2000 values)

VSL = 1 m US$	Mean (billion US$$_{2000}$)	
Warming	**Market impacts**	**Hunger impacts**
1.0	−159	1520
2.5	140	7238
4.0	494	16683
5.0	782	23140

Table 7.29: Comparison of annual market impacts and monetarized annual costs of additional hunger caused by climate change for a value of a statistical life of US$ 1 million (year 2000 values)

The result is very clear: in the agricultural sector the market impacts are very small compared to the costs of hunger. This result is so distinct, that it may be considered reliable even taking into account the vast uncertainties in this field of research.

For lower levels of temperature rise, even the direction of the impact is different: Whereas for market impacts the global average is expected to be a clear gain for a 1°C warming, the number of people at risk of hunger is already higher than in the baseline case without climate change. For low levels of temperature rise this holds for data from all sources and all assumptions with one exception: the data cited in the IPCC Fourth Assessment Report on the results from Tubiello et al. under full CO_2-fertilization. Even for this one exception, the reduction in hunger through climate change is very small compared to the losses predicted by other sources and assumptions regarding CO_2-fertilization.

For higher levels of temperature change, there is one more exception: the data from Parry et al. for full CO_2-fertilization in 2080 cited in the IPCC Report also suggests a small reduction in hunger due to climate change. But in the same study, a huge increase in hunger in the scenario without CO_2-fertilization is expected, so that on average the outlook is very dire.

8

Consequences of the results for PAGE

In the chapters above, the agricultural sector was exemplarily assessed in detail. Impacts as a function of temperature change were derived based on the impact literature compiled by the IPCC and based on the findings from natural sciences. It is beyond the scope of this dissertation to do the same for all major impact categories. Therefore, at this point of research, the hitherto used impact module in PAGE can not be replaced by the figures above. Rather, the impact module for the agricultural sector was an example to test what a different representation of the impact module based more closely on the findings of natural science could look like. To assess the significance and meaning of the results above for the PAGE model, the relationship of these results to the hitherto used impact module is assessed.

Apart from the inclusion of the possibility of catastrophic events at higher levels of global warming, two impact categories exist in PAGE: market and non-market impacts. No single agricultural sector is explicitly modelled in PAGE2002, therefore the results above can not be compared directly to the current impact representation of the sector. In order to evaluate the conclusions that can be drawn for PAGE from the results of the previous chapters, they are compared to the agricultural sectors of the studies underlying the impact sectors of PAGE. This analysis helps to deduce the rough size of the agricultural sector's contribution to the impact sectors in PAGE, and thus a rough appraisal of the new results above and their meaning for PAGE.

The parameter settings for market and non-market impacts in PAGE are mainly based on results displayed in table 19-4 of the IPCC Third Assessment Report, Working Group II (Smith et al. 2001: 940). The table is reproduced here (table 8.1).

In the first column, information compiled in the IPCC Second Assessment Report (Pearce et al. 1996) is presented. It is based on information from other studies and draws upon expert judgement (Mendelsohn et al. 2000: 553). Among these experts are the authors of the other studies cited in the table above: those by Mendelsohn et al., by Nordhaus and Boyer, and by Tol. The numbers in the first

Region	IPCC SAR	Mendelsohn et al.		Nordhaus and Boyer	Tol
	2.5 °C Warming	1.5 °C Warming	2.5 °C Warming	2.5 °C Warming	1 °C Warming[a]
North America					3.4 (1.2)
▸ United States			0.3	−0.5	
OECD Europe					3.7 (2.2)
▸ EU				−2.8	
OECD Pacific					1.0 (1.1)
▸ Japan			−0.1	−0.5	
Eastern Europe/FSU					2.0 (3.8)
▸ Eastern Europe				−0.7	
▸ Russia			11.1	0.7	
Middle East				−2.0[b]	1.1 (2.2)
Latin America					−0.1 (0.6)
▸ Brazil			−1.4		
South, Southeast Asia					−1.7 (1.1)
▸ India			−2.0	−4.9	
China			1.8	−0.2	2.1 (5.0)[c]
Africa				−3.9	−4.1 (2.2)
Developed Countries	−1.0 to −1.5	0.12	0.3		
Developing countries	−2.0 to −9.0	0.05	−0.17		
World					
▸ Output weighted	−1.5 to −2.0	0.09	0.1	−1.5	2.3 (1.0)
▸ Population weighted				−1.9	–
▸ At world average prices					−2.7 (0.8)
▸ Equity weighted					0.2 (1.3)

Notes: **a)** Figures in brackets denote standard deviation. **b)** High income countries in Organization of Petroleum Exporting countries (OPEC) **c)** China, Laos, North Korea, Vietnam

Table 8.1: Indicative world impacts, by region (% of current GDP). Estimates are incomplete, and confidence in individual numbers is very low. There is a considerable range of uncertainty around estimates. Tol's estimated standard deviations (Tol 1999) are lower bounds to real uncertainty. Figures are expressed as impacts on a society with today's economic structure, population, laws, etc.; estimates by Mendelsohn et al. (2000) denote impact on a future economy. Positive numbers denote benefits; negative numbers denote costs (Pearce et al. 1996; Tol 1999; Mendelsohn et al. 2000; Nordhaus and Boyer 2000). Table and explanations from the IPCC Third Assessment Report (Smith et al. 2001: 940).

column therefore do not stem from a module of agricultural impact representation which is independent from the other three studies cited in the table above. In the following, the agricultural impact sectors in these three other studies are briefly outlined and compared to the impact modules in PAGE as well as the results for the agricultural sector from above.

8.1 Benchmark warming for 2.5°C warming

For a meaningful comparison to the figures from the studies cited in the IPCC Third Assessment Report, the impact module in PAGE is first described in some detail: In PAGE, the impacts for a 2.5°C warming are used as the anchoring point and extended to higher temperatures with a stochastic exponential function. Therefore, the results from the three sources above (two sources reproduced in the IPCC Fourth Assessment Report and Fischer et al. 2005) for a 2.5°C warming are directly linked to the impact representation in PAGE and will be assessed in detail.

The benchmark impacts for 2.5°C warming are, like many other parameters in PAGE, stochastic inputs described by probability distribution functions. The probability distribution function for market impacts in the EU15 (the base region) has the lower bound −0.1% of GDP, the mode 0.6% of GDP, and the upper bound 1.0% of GDP. The corresponding values for non-market impacts are the lower bound 0.0% of GDP, the mode 0.7% of GDP and the upper bound 1.5% of GDP. The parameter describing the difference of climate change impacts from one region to another is also stochastic in PAGE. The impacts in other regions than the EU15 are derived from the value for the EU15 by multiplication with so-called "regional weight factors". These weight factors are stochastic. The same weight factors apply for market and non-market impacts.

Impacts are smaller than in the EU15 in the United States, Eastern Europe, China & centrally planned Asia and other OECD. They are bigger in India & South East Asia, Africa & Middle East and Latin America. For Eastern Europe, there is more than a 90% likelihood that impacts are a gain, for all other regions this is equally unlikely as for the EU15. Table 8.2 displays the weight factors for the regions other than the EU15. Tables 8.3 and 8.4 list the corresponding impact assumptions for all world regions if the mean of the stochastic weight factor is used. The mean is chosen here rather than the most likely value as it is more directly linked to the final results of the Monte Carlo analysis. The values in PAGE were developed by a mixture of expert judgement and literature input.

8.1.1 FUND

The representation of the agricultural sector in the impact module of FUND was described in very much detail in chapter 2. Therefore, only the results are displayed here in table 8.5.

	Weight factors			
Region	**Lower bound**	**Most likely value**	**Upper bound**	**Mean**
Eastern Europe	−1.0	−0.25	0.2	−0.35
USA	0.0	0.25	0.5	0.25
China and centrally planned Asia	0.0	0.1	0.5	0.2
India and South East Asia	1.5	2.0	4.0	2.5
Africa and the Middle East	1.0	1.5	3.0	1.83
Latin America	1.0	1.5	3.0	1.83
Other OECD	0.0	0.25	0.5	0.25

Table 8.2: Weight factors for the relationship of climate change impacts in Europe to other world regions; defining values for triangular probability distribution functions; positive numbers indicate costs of climate change, negative numbers gains; from PAGE2002

	Market impacts (% of GDP)		
Region	**Lower bound**	**Most likely value**	**Upper bound**
EU15	−0.10	0.60	1.00
Eastern Europe	−0.35	−0.21	0.04
USA	−0.03	0.15	0.25
China and centrally planned Asia	−0.02	0.12	0.20
India and South East Asia	−0.25	1.50	2.50
Africa and the Middle East	−0.18	1.10	1.83
Latin America	−0.18	1.10	1.83
Other OECD	−0.03	0.15	0.25

Table 8.3: A triangular probability distribution function for market impacts in the PAGE regions when the mean of the probability distribution functions for the weight factors is employed; positive numbers indicate costs of climate change, negative numbers gains; own calculations based on PAGE2002

The level of change is negative in five regions and positive in four regions. All changes are less than 1% of gross agricultural product, that is less than 0.05% of GDP (World Bank 2009b). The global average in FUND is even smaller than this.

The mean market impact derived for the agricultural sector and a 2.5°C warming in this thesis based on data from the IPCC Fourth Assessment Report is a loss of 0.26% of GDP, significantly higher than the loss in FUND. But the main difference is the inclusion of non-market damages. The results presented in this thesis are overwhelmingly dominated by the costs in the non-market sector. Therefore the

	Non-market impacts (% of GDP)		
Region	**Lower bound**	**Most likely value**	**Upper bound**
EU15	0.0	0.7	1.5
Eastern Europe	−0.53	−0.25	0.0
USA	0.0	0.18	0.38
China and centrally planned Asia	0.0	0.14	0.30
India and South East Asia	0.0	1.75	3.75
Africa and the Middle East	0.0	1.28	2.75
Latin America	0.0	1.28	2.75
Other OECD	0.0	0.18	0.38

Table 8.4: A triangular probability distribution function for non-market impacts in the PAGE regions, when the mean of the probability distribution functions for the weight factors is employed; positive numbers indicate costs of climate change, negative numbers gains; own calculations based on PAGE2002

Region	**loss of GDP (2.5°C)**
OECD-A	0.77 %
OECD-E	0.63 %
OECD-P	−0.17 %
CEE & fSU	0.54 %
ME	−0.40 %
LA	−0.85 %
S & SEA	−0.86 %
CPA	0.29 %
AFR	−0.31 %

Table 8.5: Impacts of climate change on agriculture as represented in the FUND model; negative values are losses (Tol and Heinzow 2003: table 3)

lack of representation of these costs in FUND leads to a difference in the valuation of the overall sector of significantly more than an order of magnitude.

The value from the agricultural impact sector in FUND being clearly smaller than 0.05% of GDP is not a significant contribution to the impact probability distribution functions in PAGE2002. Non-market impacts are an important factor in PAGE, but they are not represented in the agricultural sector of FUND.

8.1.2 DICE

In table 8.6, information about DICE and the regional version RICE are presented (Nordhaus and Boyer 2000). In these earlier versions of DICE and RICE, which are the basis of the results in the IPCC Third Assessment Report, the representation of the agricultural sector in the impact module relies mainly on results from Darwin et al. (1995). For two of thirteen regions, results from other sources were used, as the regional breakdown in Darwin et al. does not correspond to the regional representation in RICE. The impact figures for a doubling of the CO_2-concentration in the atmosphere are shown in table 8.6. A 2.5°C warming was then thought to be the likely temperature rise for the doubling of the CO_2-concentration (cf. Nordhaus and Boyer 2000: 74), therefore the numbers are those corresponding to the purpose at hand and were developed to describe the impacts of a 2.5°C warming.

Region	% of GDP
United States	−0.07 %
China	0.51 %
Japan	0.55 %
OECD Europe	−0.58 %
Russia	0.87 %
India	−1.54 %
Other high income	1.14 %
High income OPEC	0.00 %
Eastern Europe	−0.58 %
Middle income	−1.43 %
Lower middle income	−0.06 %
Africa	−0.06 %
Low income	−0.06 %

Table 8.6: Impacts of climate change on agriculture at CO_2-doubling as represented in the DICE/RICE model; only market impacts are represented in DICE/RICE (Nordhaus and Boyer 2000: 76)

For some of the regions the gains or losses due to climate change exceed 1% of GDP. This is considerably more than assumed in FUND. In eight regions a loss occurs, in four regions gains, and in one region the aggregated impact of climate change is zero. In five of the thirteen regions, changes of less than 0.1% of GDP occur. For the rest, the gains and losses partially offset each other. For the global effect, a calculation based on the GDP values for 1990 as given in the original source (Nordhaus and Boyer 2000: 28ff) suggests a loss of 0.17% of GDP. This value is higher than in FUND and lower than the market impact figures developed in this thesis, but clearly within the probability range. Still, it is not a major contribution to the impacts that are represented in PAGE. Non-market impacts are not included in the agricultural sector of DICE (Nordhaus and Boyer 2000: 74f).

The comparison to the estimate developed in this thesis shows that the figures for the market sector are not very far apart. The result developed in this thesis

	Agricultural market impacts (billion US$$_{1990}$)	
Region	**Ricardian model**	**Reduced-form model**
Africa	11	−131
Asia/Middle East	80	37
Latin America/Caribbean	17	−49
Western Europe	17	17
F.U.S.S.R./Eastern Europe	117	222
North America	50	83
Oceania	4	−8
Total	297	171
Total as % of GDP	0.17 %	0.10 %

Table 8.7: Impacts of climate change on agriculture for a 2°C warming (Mendelsohn et al. 2000: tables V and VI; information on the overall size of GDP from table III); positive numbers are gains

based on the latest scientific evidence from the IPCC Fourth Assessment Report is higher, but considering the uncertainties involved it is worthwhile mentioning that all results are of the same order of magnitude. However, in parallel to the findings for FUND, the numbers for the entire agricultural sector including non-market impacts presented in this thesis are a lot higher than those in DICE, because the non-market impacts dominate the overall costs of climate change in this sector and these costs are not reflected in DICE.

8.1.3 Mendelsohn et al.

In the study by Mendelsohn et al. (2000), the agricultural impact representation relies on a mix of two approaches: a reduced-form model based on laboratory experiments and a Ricardian study integrating adaptation to a wide extent (Mendelsohn et al. 2000: 557). Results are based on studies calibrated for the United States which are applied to the whole world. The results for a 2°C warming are summarized in table 8.7. Results for a 2.5°C warming are not given in the article and can not be calculated with the formulae given without detailed knowledge about the precipitation assumptions in the employed climate scenario.

The impacts in this study are largely dominated by the agricultural sector. The absolute value of the impacts from all other sectors is only between 7% and 13% of the overall impacts, or 0.01% of GDP (Mendelsohn et al. 2000: 563). Overall gains from climate change are beginning to decline for levels of global warming higher than 2°C (Mendelsohn et al. 2000: 560). But the article suggests no immediate steep decline in results that would entail clearly negative results for a 2.5°C warming. It can be assumed that the contribution to climate change impacts of the agricultural sector at 2.5°C is less than 0.1% of GDP. Non-market effects are not included (Mendelsohn et al. 2000: 567).

Similarly as for the results of the agricultural sector in FUND, the mean market impacts derived for the agricultural sector in this thesis based on data from the IPCC Fourth Assessment Report are clearly higher than the values assumed by Mendelsohn et al. But the main difference is the inclusion of non-market damages.

8.1.4 Conclusions for PAGE

The findings from these three studies suggest that the impacts in the agricultural sector did not contribute much to the impact estimates in PAGE2002 or to the values reported in the summary table from the IPCC Third Assessment Report (reproduced as table 8.1 above). The average contribution of the three agricultural impact modules at 2.5°C warming is likely to be less than 0.1% of GDP. It is not even possible to say from the findings of the three studies, whether a gain or a loss is the better description of reality. This is interesting with respect to the impact figures in PAGE that are based on the information from the IPCC Third Assessment Report. If it is attempted to separate the agricultural impact function from the general market impact function in PAGE, a correction of no more than 0.1% of GDP seems to be necessary to subtract the agricultural sector from the rest of the impact function. The results produced in this thesis based on the newest scientific compilation of data in the IPCC Fourth Assessment Report suggest that the market impacts in the agricultural sector have been underestimated in earlier studies. In light of the general uncertainties, the difference between the results here and earlier studies is not huge, however. The results from the earlier studies are within the 90%-confidence range produced in this thesis.

The case is different for the non-market impacts. Concerning the question of the role of the agricultural sector in the non-market impacts of PAGE2002, very little reliable data is available on this model input. The parameter settings therefore hinge very much on the judgement of the modeller. Here the agricultural sector plays a much more dominant role as was shown above. And although information about the magnitude of non-market impacts in the agricultural sector was not available in detail during the construction of PAGE2002, it can be assumed that the modeller Chris Hope was aware of potentially severe impacts in the realm of food scarcity. Still, the clarity with which the costs of hunger dominate the overall results in the agricultural sector has not before been demonstrated or applied in any cost calculation of the impacts of climate change.

Clearly, the non-market impacts in PAGE2002 ranging mainly between 0% and 2% (extreme values are −0.53% and 3.75%, the negative value being a gain) of GDP include impacts from other sectors as well, for example for the loss of biodiversity, cultural heritage, climate refugees, and death caused be increased storms. The non-market impacts in the agricultural sector of PAGE therefore amount to clearly less than 0% to 2% of GDP.

The mode and the mean of the monetary valuation of death caused by hunger due to a 2.5°C warming based on the value of a statistical life of 1 million € are around 6% of GDP, substantially higher than estimates currently implemented in PAGE. Of course, this figure is subject to pervasive uncertainty: the results encompass a range of 1.6% to 17.4% of GDP, and this does not reflect all uncertainties involved. But even the lower bound of this range is probably higher than the share of the agricultural sector in the non-market impacts of PAGE. And the climate change impacts including the costs of non-fatal hunger would be even higher. Therefore, the full integration of the costs of hunger would very clearly increase the impact estimates in PAGE. This result hinges crucially on the ethical assumptions made above, especially on the implementation of the Universal Declaration of Human Rights in the model, that is the principle of valuing all human lives equally. This issue can not be resolved by any modeller, relying on decision analysis or not. It is up to the problem owners to judge these ethical valuations.

8.2 Impacts for other levels of temperature increase than 2.5°C

The aim of a cost-benefit analysis is usually to facilitate the search for the optimal action, that is in this case the optimal level of temperature change. With the current data availability and the strong influence of ethical choices, not even an approximately precise estimate of the optimal level is possible. But even where no comparison of costs and benefits is ventured but just a realistic idea of the costs of climate change is sought, information of costs at different levels of warming is essential to facilitate policy-relevant conclusions from the model. The tool of a climate cost model is only used in its entire quality, when costs and benefits for different levels of temperature change can be compared, not just for 2.5°C warming. The feature to extrapolate impacts for a benchmark warming to other levels of temperature change has accordingly been implemented in all the cost-benefit models assessed above. Apart from the values for the anchoring impact estimates at benchmark warming, this extrapolation has a crucial influence on the correct representation of impacts in any model. The results for impacts in the agricultural sector at different levels of warming from the previous chapters are therefore compared to the current extrapolation mechanism in PAGE.

For a full picture of possible climate change impacts, it is necessary to track the development of impacts both above and below the benchmark temperature change of 2.5°C warming. The post-SRES scenarios cover temperature rise projections of up to 6.1°C (Barker et al. 2007: 39). For lower levels of warming a smaller temperature range is of interest. It is not easy to implement a climate policy that stabilizes the global temperature at a level far below 2.5°C above pre-industrial temperatures, which is about 1.4°C above today's temperatures (Allison et al. 2009: 11). But 2°C is the target agreed upon by many nations, and even this level of warming implies serious risks (Stern 2007: 57). Therefore both the relationships of impacts above and below 2.5°C warming to the benchmark level are regarded in the following.

In PAGE, impacts for other levels of temperature increase are derived from the benchmark impact probability distribution functions for 2.5°C warming with a power function. The exponent of the power function is once more a stochastic parameter defined by a triangular probability distribution function with lower bound 1, most likely value 1.3 and upper bound 3.

Market impacts in the agricultural sector for levels of warming less than 2.5°C are likely misrepresented by this formula. Evidence suggests that they are a gain for very small levels of temperature increase like 1°C, becoming a loss for higher temperatures. This turning point occurs before 2.5°C warming according to the findings above. The effect of zero change for zero temperature rise followed by a gain that turns into a loss for higher temperatures is not captured by a power function like the one in PAGE. The gains for very small levels of temperature increase are not represented in the model, and therefore the costs of climate change for this range of warming are likely overestimated. For a 1°C warming the calculations above suggest a market gain of 0.3% of GDP. This order of magnitude is probably missing from the impact representation in PAGE. However, this small misrepresentation can hardly be seen as a serious drawback to the model in a world where temperature rises have already reached or exceeded 1°C on land, and are not expected to fall back below that value in the next few centuries (Solomon et al. 2007: 36, 37, 71 and figure TS.29). It may only matter when current damages are compared to future damages for a certain emission path to estimate the benefit of mitigation action. But even in this case comparison to 2°C is probably a more widely used scenario, as less climate change is very ambitious. (Solomon et al. 2007: table TS.5; Fisher et al. 2007: table 3.5)

For low levels of warming, the power function in PAGE may be more realistic for non-market impacts. Here losses are expected even at low levels of warming. A power function through the points for mean non-market impacts at 2.5°C, 1°C and zero damage at 0°C is to the power of 1.7. The mean of the probability distribution function describing the power function exponent in PAGE is 1.8. This is remarkably close.

For higher levels of warming beyond 2.5°C, the power function through the three calibration points 2.5°C, 3.6°C and 4.4°C for mean market impacts has the power function exponent 2.6 (R^2=0.999). For non-market impacts, direct results are available only up to 3.1°C warming for the results from Easterling et al. (2007: 299). A trend potential trend line using only the calibration points for 0.87°C, 1.75°C and 3.1°C warming derived directly from the original source, has the impact function exponent 1.7. However, the trend line has a visibly flatter slope than the real data. These values show that the real impact function exponent is higher than 1.7, but the exact form is not known as data is available only for a very limited temperature range.

No evidence was found in the qualitative description of climate change impacts in the agricultural sector that yield losses increase faster than hunger with rising temperatures. It can not be excluded, that the difference is caused by the large uncertainties and different calculation procedures for the different sub-sectors, both in the underlying studies and in this thesis. This is not unlikely as very little is reliably known about the higher temperature impacts on hunger. The important result here is, that the impact function exponent seems to be roughly in the range suggested and implemented in PAGE2002 – probably it should be somewhat higher. For market impacts, the best guess estimate for the impact function exponent for temperatures above 2.5°C is 2.6, compared to 1.8 in PAGE.

8.3 Adaptation

The integration of adaptation in cost models of climate change is another difficult part of impact representation. No comprehensive estimates exist on the costs and benefits of adaptation. There are substantial limits and barriers to adaptation, but it would distort the impact representation in a model to completely ignore the role of adaptation. (Adger et al. 2007: 719)

In the following, it is assessed how much is known about adaptation options and costs in the agricultural sector, and in how far adaptation has been integrated in the impact estimates from the previous chapters.

8.3.1 Market impacts

A range of adaptation options was simulated in some of the studies cited in the IPCC Report. They include: changes in planting, changes in cultivar, and shifts from rain-fed to irrigated conditions. More adaptation options are conceivable. For example, shifting to different cultivars of the same grain was included as an adaptation option by some of the studies underlying the results above, but the possibility to switch for example from wheat to rice was not considered. Therefore some further adaptation potential is possible.

It is not in line with the structure of PAGE that some adaptation potential is already captured in the yield change results above. The usual concept in PAGE is to identify the adaptation potential separately from the climate change impacts. In the PAGE model, a separate feature for the inclusion of adaptation exists. However, as little general knowledge is available about the potentials of adaptation, it was deemed an unnecessary loss of information to exclude the studies with adaptation from the previous analysis. It would have been possible to use only the studies without adaptation for the results above and try to deduce information about the average potential of adaptation from the difference of studies with and without adaptation. But the adaptation options included differ widely and are not sufficiently marked in the text. Therefore any numerical inference from the data would have been very vague. Indeed, that may be the reason that no numerical adaptation estimates are given in the IPCC Report. It was therefore preferred to use the information from the studies with adaptation as well and thus integrate the implicit knowledge about adaptation. But this means, that in the structure of PAGE only adaptation potentials beyond what is already included in the data above should be especially regarded in the model's adaptation feature.

For market impacts in PAGE2002, the default value for the proportion of damages avoided through adaptation is 90% in industrialised countries and 50% in developing countries from 2020 onwards. Before that date, the fraction of damages avoided is smaller. It is assumed likely that in the agricultural sector the adaptation potential that may exist above the measures included in the IPCC data is a lot smaller than these values implemented as default values in PAGE2002. In the agricultural sector, adaptation is predicted to become more difficult for higher temperatures. A lot of yield losses are caused by more intensive extreme weather events that lead to drought or floods. These losses can only to a limited extent be avoided by a shift to a different crop. Even more difficult to avoid are yield losses because of area lost to sea-level rise. These losses are usually not even accounted for in the yield change studies, but large scale adaptation is extremely difficult for scenarios of high sea-level rise. Many other adaptation options are already partially included in the data reported in the IPCC Fourth Assessment Report. Therefore the necessity for further inclusion of adaptation is limited. Exact figures are not available. A rather wide range of 0–50% could reflect the considerations above. But 90% (industrialised countries) and 50% (developing countries) of damages in the market sector avoided through adaptation as implemented in PAGE is probably too high a value for the agricultural sector.

8.3.2 Non-market impacts

In the default version of PAGE2002, the adaptation potential for non-market damages is lower than for market impacts. From the year 2020 onwards, 25% are assumed all over the world. For people at risk of hunger it is doubtful, whether even this value can be reached. People who are starving are the very poor people, who have extremely scarce or no resources available to invest into adaptation measures. Adaptation potential therefore hinges to a major extent on the will of the international community to combat hunger. In the past, this has not avoided hunger to be a very widespread and growing phenomenon on our planet. One billion people are undernourished in 2009 (FAO 2009b: 11). Because of the strong influence of political decisions, it is considered difficult to assume a general percentage of impacts avoided through adaptation for the subcategory of ‘people at risk of hunger’. What can be said is that the adaptation potential in PAGE has probably not been underestimated where hunger is concerned.

8.4 Conclusions for the further use of PAGE

The impact figures derived above show that it is possible to develop impact figures that are better in accordance with decision analysis. It is certainly easier to capture the knowledge and uncertainties of climate change impacts from the analysis based on IPCC data above than in the highly aggregated impact categories in PAGE2002. From this point of view, a sectoral representation of impacts would be a clear improvement. Furthermore, the impact representation above is considered not to be too complicated to impede comprehensibility of the model. Anyone who wishes to understand the exact development of the numbers can read the description in this thesis, otherwise the foundation on IPCC reports makes it possible to know about the provenance of the data without going into every detail. Therefore the single sector representation is found to be better in line with the principles of decision analysis than highly aggregated impact modules. This result suggests that it would be interesting to do a more detailed impact analysis for other sectors as well.

Still, even if all impact sectors were represented likewise in a climate cost model based on decision analysis, some major caveats remain to the quantification of the costs of climate change. The determination of the value of a statistical life is fraught with difficulties, especially at a global scale. The same is true for the monetisation of other non-market impacts like loss in biodiversity or the suffering of climate refugees. Nor is uncertainty eliminated with such a more detailed analysis or it can be expected that all impacts can be comprehensively covered. At least nobody could ever be sure to have a complete model and know about all the impacts. For example the rising acidity in oceans due to CO_2 dissolving in the water and the consequences for maritime ecosystems has long not been integrated in models of the costs of climate change, although this impact is potentially important (Allison et al. 2009: 36). And a thorough sectoral impact representation is a rather complicated and time-consuming procedure. It should be decided specifically and in the context of coming up research questions, whether such an effort would be worth the results that can be obtained from a climate change cost model. Therefore, hypothesis 3 is only accepted with the restriction that practicability of a sector-wise approach should equally be regarded, although the disaggregated impact module was found to improve the concordance of PAGE with the principles of decision analysis.

Maybe an alternative would be to assess single impact sectors as new evidence suggests the necessity of an update, and to integrate the corresponding results into the current structure of PAGE. Sensitivity analysis remains a very important tool, and taking the upper bounds of results seriously may prevent nasty surprises in the future. For the concept of decision analysis, a direct foundation of the impact sector representation on IPCC sectoral impact results would be very helpful.

Finally, the detailed description and assessment of the agricultural sector based on the latest IPCC Assessment Report has demonstrated that for this special sector the impact formula for the non-market sector is crucial. The omission of hunger as a very serious and large contribution to climate change impacts in earlier integrated assessment studies of climate change affects also PAGE, albeit to a lesser extent.

This is quite natural, as the impact representation in PAGE builds upon results from other studies and models.

8.5 PAGE09

In parallel with work on this thesis, a new version of PAGE was finished, the model PAGE09 (publications forthcoming). Therefore it was unfortunately not possible to include this new model version here. It may differ with respect to some of the results above based on PAGE2002 and may have resolved some of the issues raised here, but it is not likely to affect the general findings of this thesis.

9

General appraisal of PAGE2002 in light of the results above and recent scientific findings

The impact representation, but also other features of the model PAGE2002, which was used as a basic analysis tool in the Stern Review, have been analysed in much detail in this thesis. In the following, a few findings about the model are summarized:

9.1 A model based on decision analysis

PAGE2002 is a model based on decision analysis. Although the representation of the impact sector is too opaque to really live up to the basic conditions of decision analysis, the model has contributed significantly to a better understanding of the uncertainties involved in the assessment of climate change costs. The lack of precise knowledge is clearly flagged in the model and the representation of model results. This is a very valuable feature considering the extent of the uncertainties involved. Model users have the possibility to use the input parameters that best fit their own judgement.

9.2 Comparison to the most recent scientific findings

In the last chapters, the possible representation of up-to-date knowledge on climate change impacts in the agricultural sector was assessed. These findings were related to the impact representation in PAGE2002 and also to the default parameter settings in PAGE2002. Since the construction of PAGE2002, research has advanced the knowledge about other aspects of climate change that are represented in the model. It is interesting to see, whether PAGE2002 with its default parameter setting rather overestimates or underestimates climate change damages compared to the most up-to-date knowledge. Stern himself suggested in November 2009 that recent developments in climate change sciences are reason to be more pessimistic than at the time when the Stern Review was published (Balser and Bauchmüller 2009: 26).

Five main scientific fields contribute to the calculation of climate change impacts in PAGE2002:

- The climate module describing the atmospheric processes
- The socio-economic scenario
- Impact representation
- Adaptation assumptions
- Ethical assumptions about discounting and equity weighting

In the following, for each of these fields, up-to-date scientific knowledge from the IPCC Fourth Assessment Report or more recent sources is compared to the default parameter settings in PAGE. The question to be answered is whether impacts have been rather over- or underestimated in PAGE2002 with its default parameter setting.

9.2.1 The climate module describing the atmospheric processes

The representation of the atmospheric processes in PAGE2002 is very close to the IPCC SRES scenarios. The difference of the best guess curves for the global mean temperature change over this century from the SRES curves is almost indiscernible (Hope 2006: 28). But the post-SRES scenarios suggest that global warming may be faster and stronger than previously thought (Fisher et al. 2007: 198). The warming projections of the different scenarios were compared in detail in table 7.6 on page 170. These advances in science suggest that climate change impacts may be considerably higher for a given greenhouse gas emission than previously thought.

9.2.2 The socio-economic scenario

The main version of PAGE2002 follows the IPCC SRES A2 scenario. Not very many years have passed since the construction of PAGE2002 to allow a better judgement of future projections that reach out over a whole century – or even two as in PAGE. But recent knowledge about the development of fossil fuel emissions gained over the last decade gives reason to assume that in absence of stringent climate policies the emissions grow even faster than previously thought. Figure 9.1 compares the emission assumptions of the SRES scenarios with the real development.

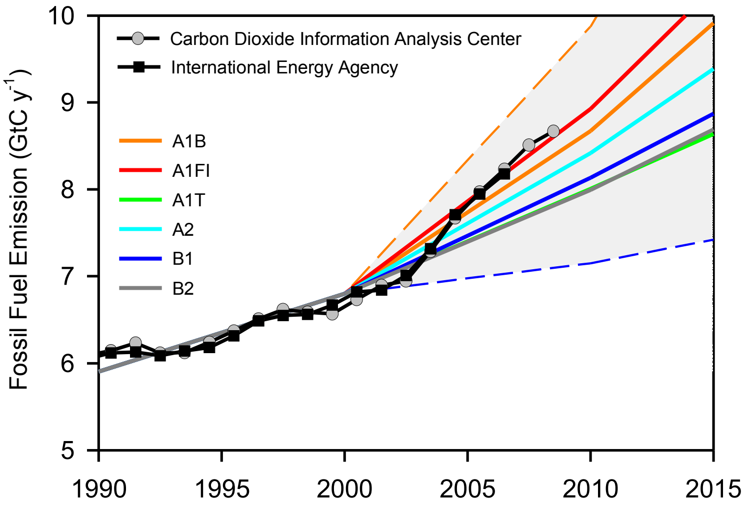

Figure 9.1: Fossil fuel emissions: actual versus IPCC scenarios; (Global Carbon Project 2009: 14)

On the one hand, this fast emission growth suggests that the climate change damages in PAGE2002 have been underestimated rather than overestimated when the newest scientific evidence is taken into consideration: real emission growth was faster than assumed in the A2 scenario. On the other hand, the long term population growth assumptions in PAGE2002 may be too pessimistic. It was assumed, that population growth continues at significant levels throughout the 22nd century, leading to a global population of 21 billion in 2200. Current UN projections expect a long-term stabilisation at around 9 billion people (UN 2004: 1). The population assumptions are important for the results in the PAGE model, they even affect the discounting.

9.2.3 Impact representation

This part of the model has been examined in detail for the agricultural sector in the chapters above. Especially the findings for the non-market damages suggest that the impact data taken for the default parameter setting from a compilation in the IPCC Third Assessment Report may have been a significant underestimate of true damages. The damage expectations from other sectors have not been reduced either since the publication of the IPCC Third Assessment Report. On the contrary, some potential damages have been brought into the focus of the debate which were not included in the compilation of damage estimates in the IPCC Third Assessment Report. For example, the acidification of the oceans caused by higher levels of atmospheric CO_2 and consequently more CO_2 dissolved in the oceans is a serious threat to many oceanic ecosystems (Allison et al. 2009: 36). The recent developments in the science of climate change impacts thus suggest, that climate change damages may be higher than thought in 2002.

9.2.4 Adaptation assumptions

The adaptation assumptions in the default version of PAGE2002 have been explained in chapter 8.3. It was shown that these assumptions are rather too optimistic for the agricultural sector. All in all, the assumption that 90% of market damages can be avoided through adaptation in industrialised countries seems rather optimistic. In the IPCC Fourth Assessment Report, it is stated with very high confidence that substantial limits and barriers exist to adaptation (Adger et al. 2007: 719) Furthermore, adaptation and adjustment costs may be higher than assumed in the model (Lorenzoni and Adger 2006). In light of recent scientific findings, it can therefore be assumed that this part of the PAGE2002 model leads to an underestimate of damages rather than an overestimate.

9.2.5 Ethical assumptions

Ethical assumptions can by their nature not be judged objectively, and therefore no assessment is possible here, whether recent progress in science suggests higher or lower numbers for the costs of climate change. It can be said that the main changes to PAGE effectuated in the Stern Review were the introduction of a different discounting scheme and of a longer time scale, leading to a higher estimate of the costs of climate change. As explained above, the main discounting factor in PAGE is the rate of pure time preference.

Another ethical decision is the use of equity weighting. Equity weighting in PAGE can not include intraregional wealth differences. Total impact results without equity weighting are about 75% of impacts with inter-regional equity weighting in PAGE (own calculations on basis of PAGE2002).

9.2.6 Aggregation of the five model parts assessed above

Only one piece of evidence was found to support the assumption that the scientific development since the construction of PAGE2002 suggests lower damages of climate change than assumed earlier: the population development in the 22nd century seems rather pessimistic compared to current projections. All other factors identified above support the opposite assumption: that recent findings in climate change sciences are even more alarming than earlier publications suggested. Several of these factors demonstrate that the results from PAGE2002 with its default parameter settings are an underestimate of true climate change damages: the valuation of hunger, recent warming projections for a given greenhouse gas concentration in the atmosphere, and the estimation of adaptation potentials.

This has implications for the results in the Stern Review as well. All model parts examined above except the discounting mechanism were used directly for the calculation of the impact figures reported in the Stern Review. Therefore the conclusion that climate change damages have been underestimated rather than overestimated in PAGE2002 equally applies to the Stern Review. This does not touch upon the influence of DYNASTY, the add on model from the Stern team which has not been assessed here.

Conclusions

10

10.1 The hypotheses

Two hypotheses were presented at the beginning of the thesis and consequently tested. Hypothesis 1 and 2 were:

Hypothesis 1:
In cost models of climate change, an approach striving for maximal objectivity does not (yet) yield meaningful results for the estimation of the costs of climate change. Apart from the necessity for ethical inputs into the model, this is due to the pervasive uncertainties which force the modeller to introduce his or her own judgement into the model. The extent of this uncertainty is so large, that the claim to objectivity ceases to be meaningful.

Hypothesis 2:
To avoid a false impression of objectivity and certainty, decision analysis was chosen as the theoretical foundation for the integrated assessment model PAGE. But although the model PAGE is not subject to some of the common problems in dealing with uncertainty, it does not live up to the standards of its underlying theory: decision analysis.

Concerning hypothesis 1, there was strong evidence that meaningful objectivity is not possible. A probability distribution function was developed to describe the uncertainty of the estimate. The standard deviation of this probability distribution function of welfare change in the agricultural sector triggered by a 2.5° warming is between 5 and 27 times the welfare change itself, depending on the region. The 95%-confidence interval therefore encompasses a range 20 to 108 times as big as the absolute welfare changes assumed for a 2.5°C warming in FUND. Figure 10.1 illustrates this wide uncertainty range.

Uncertainty further increases for higher temperatures. And in this estimate, not all sources of uncertainty are included. Furthermore, calculations were performed

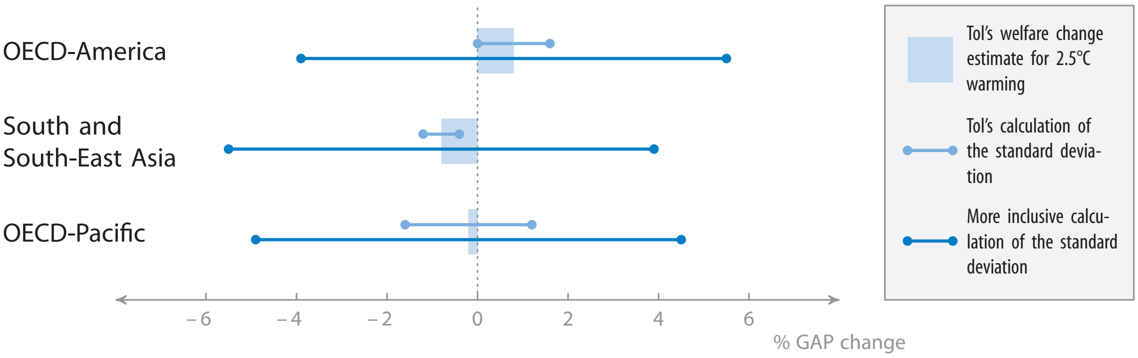

Figure 10.1: Uncertainty described as the standard deviation of a probability distribution function and compared to the absolute welfare change for 2.5°C warming in FUND

in a conservative fashion so as not to overestimate uncertainty. There is little reason to assume, that DICE performs better in this respect, as FUND is based on a wider range of studies, mainly including those used in DICE. Therefore, uncertainty in climate cost models is so substantial that the models can hardly be a good decision aid to problem owners who do not understand the sources and scope of uncertainty and can not use their own judgement how to deal with these uncertainties. Hypothesis 1 is accepted.

Concerning hypothesis 2, an analysis of the implementation of decision analysis in the PAGE model was done. The aim of a model based on decision analysis is to facilitate the judgement of uncertainty to the problem owners and supply them with a model where they can test the consequences of their own beliefs and valuations. The principles of decision analysis were listed and the realization of the theoretical concept in the model PAGE2002 was assessed:

On the one hand, in line with the requirements of decision analysis, uncertainty is very openly flagged in PAGE as well as integrated via a probabilistic approach. Easy access to the model is assured. And the probabilistic approach delivers valuable information on possible ranges of results. Therefore, the theory of decision analysis has triggered important improvements in the model.

But PAGE2002 does not fully live up to the requirement of interactive model building involving both the modeller and the decision makers. Above all, the impact representation in PAGE is so abstract that model users can not judge the accuracy according to their own beliefs and opinions. The parameter settings for the impact sector have such an important influence on the final result that this shortcoming fundamentally impairs the concordance with the principles of decision analysis. Hypothesis 2 is accepted.

Thus, both theoretical concepts of dealing with uncertainty in climate cost models assessed in this thesis were found to imply profound difficulties: the approach striving for maximal objectivity and the approach based on decision analysis as defined above. It is sensible to accept that the possibility for an objective model is not given. In this sense the application of decision analysis is a promising approach. But climate change is such a complex phenomenon, that in reality only the scientific expert community has the chance to change more than a few parameters in the model. The Stern Review is an example for politically guided research by experts from science, which applied a few rather fundamental changes to the model, but did not attempt to adapt the majority of model parameters.

Therefore, paradoxically, the usefulness of cost models of climate change based on decision analysis also depends on a maximum of objectivity, as no user will adapt all assumptions according to personal judgement. This does sound paradox: on the one hand, the uncertainty analysis in part 1 supports the assumption that meaningful objectivity of climate cost models is not possible. On the other hand, a climate cost model based on decision analysis – a theory explicitly chosen to accommodate the impossibility of objectivity – also relies on the parameters being chosen as objectively as possible. The result underlines the fact that an entirely satisfying calculation of the costs of climate change is until today not possible, but it also shows that some elements from both underlying theoretical concepts are necessary for a useful model of the costs of climate change.

It is important that the foundation in state of the art science of all parts of the model is as reliable as possible, although objectivity is not possible. Knowledge from the IPCC Reports is a good data basis, because here the insight from several thousand scientists is brought together. This reduces the personal influence of single persons. Furthermore, it is the scientific institution closest to providing a consensus which incorporates also the political arena, offering a basis for policy-relevant advice. But in the impact sector, only for a small part of the impacts reliable figures are available. This underlines the necessity to openly flag uncertainties. A probabilistic approach is a possibility to do this.

Furthermore, it is necessary to regard both available data and qualitative knowledge. It was shown in this thesis that the application of data from the literature in straightforward mathematical formulae can lead to quite counterintuitive results. This was the case for agricultural impact functions in some of the FUND regions that suggest increasingly rising benefits from climate change after losses for very low levels of temperature rise. In such a case, it is recommended to trust rather the qualitative knowledge presented in the IPCC reports than single numerical outcomes. Uncertain inputs can lead to major errors where threshold effects exist in the modelling. Plausibility scrutiny for all kinds of model results is therefore crucial. If the limits and possibilities of decision analysis are recognized, the application of its principles is found to be an improvement over an approach solely striving for objectivity.

From these results in the context of hypotheses 1 and 2, hypothesis 3 was developed. Hypothesis 3 deals with the question whether impact representation in single sectors like the agricultural sector is meaningfully possible and could improve the shortcomings of PAGE with respect to the principles of decision analysis:

Hypothesis 3:
An impact representation split into single sectors and founded in up to date scientific impact research as presented in the IPCC Reports helps to overcome the major shortcoming of PAGE with respect to decision analysis. Sectoral impact figures facilitate the decision makers' judgement whether they agree with the impact assumptions in the model.

To test hypothesis 3, agricultural impact data for the market sector and for people at risk of hunger was taken from the IPCC Fourth Assessment Report. These show that it is possible to develop impact modules that are better in accordance with decision analysis. It is certainly easier to capture the knowledge and uncertainties of climate change impacts from the analysis based on IPCC data above than in the highly aggregated impact categories in PAGE2002. From this point of view, a sectoral representation of impacts is a clear improvement. Furthermore, the impact representation above is considered not to be too complicated to impede comprehensibility of the model. The description in this thesis can be used as a tool to understand the exact development of the numbers; the foundation on IPCC reports makes it possible to know about the provenance of the data without going into every detail. Ethical assumptions are openly presented. Major issues are the valuation of market and especially non-market impacts and discounting. For the impact data above, changes to the ethical default assumptions are comparatively easily possible. Therefore the single sector representation is better in line with the theoretical concept of decision analysis than highly aggregated impact modules.

Still, it was found that quite a number of adaptations are necessary to the data reported by the IPCC to make it an adequate input to the PAGE model. If all impact sectors were represented in PAGE at an equal level of detail that allows ethical assumptions to be sufficiently separated, the entire model would need to be large and complex. The single impact study for the agricultural sector is already quite voluminous. A lot of such impact assessments at the necessary level of detail to comply with the principles of decision analysis might surpass the capacity or time constraints of most model users for an understanding of the entire model. Most of them would probably only look at a few impact sectors and might decide to trust the model if the ethical and uncertainty assumptions there comply with their personal opinion. But this shows very clearly, that an improvement with respect to one principle of decision analysis (integrate ethical assumptions and uncertainty beliefs of problem owners) comes at the cost of losing ground with respect to another principle (simplicity).

Furthermore, a thorough sectoral impact representation is a lot of work. It should be decided specifically and in the context of coming up research questions, whether such an effort would be worth the results that can be obtained from a climate change cost model. Hypothesis 3 is only accepted with an important limitation: the sectoral impact module is a clear improvement, but it comes at the price of a significantly more complex model. General recommendations are not adequate.

10.2 The costs of climate change in the agricultural sector

Insight about the costs of climate change was gained from the sectoral impact data developed above. For market and especially for non-market impacts the monetisation of the impact figures is very difficult and fraught with subjectivity. For the numbers of additional people dying from the consequences of hunger, it is recommended to use these figures directly and without a further step of monetisation whenever possible. To express the value of human lives lost in terms of money is very problematic on ethical grounds. The dissent on suitable numbers is even more pronounced when the issue involves world regions with very different levels of per capita income.

In case anybody notwithstanding wishes to do a direct numerical comparison of the market and the non-market sectors, a common metric is necessary. A survey of the literature on the costs of a statistical life shows that not enough data is available to use local values and subsequently add a scheme for equity weighting. Therefore available knowledge was used to derive an average global value for a statistical life. This is extremely subjective, and the value was chosen in a way that makes it especially easy for problem owners to integrate their personal assumptions about this measure.

The valuation of market impacts hinges crucially on the assumptions about the effects of global trade, the method to deal with demand not apparent in the demand curve, and the second best measure chosen to approximate the unknown changes in consumer and producer surplus. The latter can not be quantified as the demand and supply curve can not be determined empirically or otherwise in all necessary parts, that is at all points to the left of the market equilibrium. It was shown that changes in gross agricultural product and yield as alternative welfare measures likely underestimate the changes in consumer and producer surplus. In this thesis, the change in productivity was used to approximate welfare changes. This quantity is higher than the gross changes in agricultural product and yield, maybe higher than the loss in consumer and producer surplus. But not all demand is reflected in the demand curve, as an assessment of subsistence farming and low-income consumers showed. This can lead to severe underestimates of true welfare losses.

The inclusion of global trade via global equilibrium models equally underestimates true welfare losses, as poor countries are expected to suffer the biggest yield losses. It is openly admitted that productivity changes are no perfect approximation, equally as no other method is perfect. The overall error induced by this assumption is insignificant, however, when market and non-market losses are added up. The latter dominate so clearly for all market welfare measures discussed above and in the literature, that the assumption about the best welfare measure for market impacts does not significantly influence the final result.

For the comparison of market and non-market monetarized costs shows very clearly that the overall costs of climate change in the agricultural sector are dominated by the costs of hunger. This is even true when the costs of non-fatal hunger are disregarded and with very optimistic assumptions about the hunger caused by climate change. Ethical judgements and uncertainties are crucial and not all have been captured in the analysis. But the picture is clear enough to call the result robust, especially as many major uncertainties like the effect of CO_2-fertilization equally affect market and non-market impacts and can not fundamentally change the relationship between the two.

Therefore, accuracy in the calculation of market costs in the agricultural sector is useless for cost-benefit analysis when the much more important contribution to overall costs is neglected and ignored. Still, this is exactly what a lot of traditional climate cost models do. It can not be an argument that the costs of hunger are more difficult to calculate than the market costs of yield losses. It is true that the costs of hunger are very difficult to calculate, that they can only be estimated with a high level of uncertainty, and that they are substantially influenced by ethical decisions. But their omission is certainly and beyond doubt a serious error in any calculation of the costs of climate change. It is an advantage of decision analysis that ethical assumptions are openly flagged rather than to drop the impact altogether because objectivity is not possible.

These results suggest that without an assumption about the value of a statistical life and the inclusion of the non-market sector, no meaningful cost-benefit comparison of climate change mitigation levels relying on one metric is possible. The valuation of market costs of climate change is still an interesting piece of information, but it is not useful to compare a part of the benefits of mitigation to the entire costs and derive from this comparison a recommendation for the optimal level of mitigation.

Whenever it is known whether the omitted impacts are a gain or a loss, cost-benefit analysis can indicate a lower or upper bound of rational mitigation intensity, even without including all major impacts. In case of the agricultural sector, there is very strong evidence that the non-market impacts are negative and very significant. Therefore, models that do not include the non-market impacts of climate change in the agricultural sector show that more mitigation is rational than the cost-benefit analysis suggests at first sight. For a reliable conclusion, it would need to be judged for all other major omitted impacts whether they are a gain or a loss. In a model based on decision analysis, the problem owners should decide what kind of risk or chance they attach to impacts that are so far not recognized at all.

A meaningful representation of reality in the impact module is a major challenge, and how this challenge is solved has a crucial importance for the quality of the model. The uncertainties in the impact modules are pervasive and large knowledge gaps persist around this part of climate cost models. When integrated assessment models of climate change are used, a lot of openness on possible error sources and thought on the impact sector in general is necessary. High sophistication and precision on other model parts is useless as long as the impact sector is characterized by very high uncertainties.

Considering the scope of the difficulties involved, it is recommended not to rely on cost estimates only for decision making on climate change. Although models of the costs of climate change can provide interesting insight into the economic dimensions of the problem and can be an interesting additional piece of information, they can hardly be reliable enough to replace other decision procedures on the optimal level of climate change mitigation.

10.3 The impact module in PAGE2002

Concerning the impact sector in PAGE, the above results suggest that the market impacts have been slightly underestimated in PAGE2002 with its default parameter settings, and the non-market impacts have been significantly underestimated. An increase of the input parameter for non-market impacts at 2.5°C warming is recommended. For the impact function exponent, the IPCC data evaluated above suggest that the range seems to be remarkably close to reality for non-market impacts, but probably a little too low for market impacts. Uncertainty is still high on these parameters, however. Especially for non-market impacts no reliable data on higher temperatures is available and there is reason to assume that a higher impact function exponent would be adequate for higher temperatures.

Finally, all major components of the model PAGE2002 with its default parameter settings were tested against the latest scientific evidence from climate change sciences as compiled in the IPCC Fourth Assessment Report or later publications. It was attempted to judge whether the recent developments in climate sciences rather lead to a more pessimistic or more optimistic outlook on the costs of climate change. Five main scientific fields were identified that are integrated into one model in PAGE:

- The climate module describing the atmospheric processes
- The socio-economic scenario
- Impact representation
- Adaptation assumptions
- Ethical assumptions – utility comparison

Only one factor was found in the whole assessment where recent scientific findings suggest a more optimistic outlook on the costs of climate change: the assumptions with regard to population growth are rather pessimistic. But several scientific developments show that climate change is more dangerous than previously thought: the development of greenhouse gas emissions, the impact parameters, the adaptation assumptions and the parameter for climate sensitivity. Therefore the true costs of climate change are very likely even higher than calculated in PAGE2002 with its default parameter settings.

This applies equally to the results presented in the Stern Review. The numbers in the Stern Review have been derived with a combination of PAGE and an add-on called DYNASTY. It was beyond the scope of this dissertation to assess DYNASTY in detail as well. DYNASTY comprises the welfare calculations of the combined model. If in PAGE climate change costs are underestimated, this underestimate enters the DYNASTY model directly and leads to a likewise distortion in the overall result.

The results from this thesis suggest that the estimates presented in the Stern Review may rather have been an underestimate of the true costs of climate change. This is very significant: The results from the Stern Review show that a lot more mitigation action than currently implemented is economically rational. Stern and his team have been strongly criticised after the publication of their Review On the Economics of Climate Change for overestimating the costs of climate change. But their clear call for more mitigation is underlined and strengthened by the results of this thesis.

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