Ocean Economy

Implementing damages to marine sectors and ecosystems into the DICE model

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Abstract

The oceans are a key element in our society, economy and environmental system. They cover over 70% of the world's surface and contribute substantially to ecosystem services such as climate management as well as to economic sectors such as food production and tourism. While the importance of the oceans for climate change and the society is generally acknowledged in science and literature, it is often not reflected in policy. Integrated Assessment Models (IAMs) which are used to advice policy on carbon prices often systematically omit process and damages related to the ocean such as ocean acidification, loss of biodiversity and changes in ocean currents.

The aim of this study is to give a more detailed perspective on ocean related processes and their role and importance for the economy under climate change and to test assumptions made in the development of IAMs - and more precisely the Dynamic Integrated Climate-Economy model also referred to as the DICE model. The initial results of the DICE model resulted in an optimal temperature trajectory with a maximum of 4 °C contradicting the goals set with the Paris Agreement.

This thesis is the first of its kind attempt in reviewing the most recent biophysical evidence on climate change impacts with a focus on marine systems and incorporating these damages to market and non-market sectors into the DICE model. The impacts from climate change are implemented into the DICE model through economic valuation of the damages and an update of the damage function. The analysis is based on the damage function used in the original DICE2016R2 model as well as the suggested update presented by Hänsel et al. (2020)

The results show, that incorporating marine damages into the model yields in a major increase in economic damages particularly in the temperature range up to 2°C. These increased damages influence the results of the optimal temperature trajectory and give a clear indication for a more stringent climate policy, drastically limiting the maximum temperature increase compared to the original DICE model.
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1 Introduction

Climate change is one of the most pressing and critical issues of modern times which will influence how our planet and society will evolve in the foreseeable future. In contrast to other defining impacts such as conflicts, diseases or financial recessions, climate change has a global impact to which virtually every person in the past and present on this planet contributed in their everyday life. Furthermore, the time horizon in which climate change will have an effect is much longer, spanning several centuries with a considerable time lack.

The oceans are a global system covering around 70% of the earth’s surface, providing food, livelihoods as well as cultural value to humanity and being a major influence on the world’s climate. Oceans have a major impact on the climate and climate change through their physical and chemical relation with the atmosphere as well as through the rich biodiversity contained within the oceans. However, the impact of climate change on the ocean and its ecosystems is poorly visible and some areas such as ocean acidification have only been discovered recently and are not yet well understood in detail. These circumstances lead to the fact that the mitigation of effects from climate change on the oceans as well as ocean protection is a rather neglected and possibly underestimated issue. This is for instance illustrated by the fact the Sustainable Development Goal 14 “Life Below Water” established by the UN is the most underfunded goal of all SDGs.

The impact of climate change on the oceans is often not considered in detail in economic and climate modelling. Among others, this is the case for the DICE model developed by Nobel laureate William Nordhaus. The DICE model is next to the FUND and PAGE model one of the major Integrated Assessment Models (IAM) which links economic development to climate change. The model is used by governmental institutions such as the US Environmental Protection Agency, the US Office of Management and Budget as well as the IPCC for advising on policies such as carbon prices (W. Nordhaus 2014). One of the key elements within IAMs is the damage function which determines the assumed economic damage in relation to the increase in atmospheric temperature. The results from IAMs are highly sensitive to the form of the damage function and it’s underlying assumptions. With the assumed damage function included in the latest version of the DICE model,
computed optimal temperature paths found contradicting results to the goals set out in the Paris Agreement with an optimal temperature increase of about 4.1 °C.

In current models a significant amount of damages to the marine economy and ecosystems such as ocean acidification, loss of biodiversity and shifts in ocean currents are either omitted or considered with crude assumptions. The aim of this thesis is to give a better perspective on the oceans as a player related to climate change and the effects of changing oceans on our society. For this purpose, the damages related to the oceans will be investigated by reviewing the most recent literature on biophysical impacts from climate change on marine systems. The oceans are a particular environment, where most of the damages by climate change affect ecosystems and non-market goods - ergo commodities which are not traded on the market and for which we therefore do not have a common market price which could be accounted. Nevertheless, these ecosystems represent a considerable value for the human society through functions such as provisions services erosion prevention, regulatory services and maintenance services. For an implementation of these damages - which are often related to non-market damages - the economic output in the DICE model is extended to include non-market outputs. For this purpose the framework suggested by Dasgupta (2021) is used.

The damage function included in the current version of the DICE model as well as the damage function used in a later update by Hänsel et al. (2020) will be updated with the literature based evidence. The impacts of these changes on the results of the DICE model show a significant decrease in the maximum temperature increase for the original DICE version supporting the goals of the Paris agreement. However, sensitivity issues and high variations in the Social Cost of Carbon (SCC) as well as barriers in implementing non-market damages remain. These areas are identified as main knowledge gaps and further research is needed in order to make the here presented research ready for implementation.
2 Economic and Climate Modelling

The following section will describe some basic economic backgrounds as well as how climate change is implemented into economic models.

Our society, the economy and climate change are subjects which are closely interlinked between each other. The extend of climate change is largely depending on economic development and economic transformation processes such as the decoupling of economic output from $CO_2$ emissions. At the same time, climate change effects the economic output through damages to capital including natural capital and ecosystem services. In order to estimate costs from climate change on the economy and to inform on economically sound investments into climate mitigation, Integrated Assessment Models (IAMs) have been developed. These models depict the circular relationship between economic development and climate change and are often used as a tool within policy making.

2.1 Background on Economic and Climate Modelling

There are several models commonly used for climate policy. The three models used for comparison and determination of climate policy for instance by the U.S. government are the FUND, PAGE and the DICE model. The following analysis will focus on the DICE model.

2.2 The DICE Model

The DICE (Dynamic Integrated model of Climate and Economy) is an Integrated Assessment Model (IAM). The model has been mainly developed by William Nordhaus, who started to develop the model in 1990 (W. Nordhaus and Sztorc 2013). Since then the model has gone through several revisions following updates on economic development, climate research and related disciplines. The latest fully updated version, which serves as a basis for this thesis is DICE2016R2. Nordhaus was awarded with the Nobel price for his work and achievements in climate and economic modelling in 2018.

The DICE model is an Integrated Assessment Model meaning that it links economic activities to climate change and vice versa. Economic activities in our economy as
of today are related to the emission of Carbon Dioxide (CO$_2$) and therefore impact the climate through radiative forcing. A detailed discussion of the physical processes underlying climate change can be found in Hsiang and Kopp (2018).

However, the changing climate comes with several effects on our society and economy which are to the largest extend negative. The idea of IAMs is to model economic development, the resulting climate response and its effects on the economy measured in costs or loss of GDP and therefore connect several disciplines such as climate sciences, ecology, economics as well as political science (W. Nordhaus 2019). With this approach the ultimate goal of the model is to give an indication on how much should be invested in order to mitigate climate change and therefore prevent overproportional damages from climate change.

### 2.2.1 Economic Theory and Background

The DICE model is based on several economic theories and addresses market failures. The aim of this section is to provide some insights into underlying economic theory and important concepts to understand how the DICE model works.

An important aspect in the context of climate change is the concept of externalities. These describe a scenario in which the costs or effects of a certain process are not reflected in the actual market price of this process. This reflects the situation where the emission of CO$_2$ is free of charge for those that emit while those that are harmed are not compensated. The case of CO$_2$ is a particularly difficult externality since it involves virtually all economically relevant processes, has a long time impact and impacts the global population, while impacts are not distributed evenly (W. Nordhaus 2013).

The DICE model and its perspective on the economics of climate change is based on neoclassical economic growth theory (W. Nordhaus and Sztorc 2013), where through investments in climate change mitigation, the ability for consumption in the present is reduced in order to increase consumption in the future. The DICE model incorporates this approach by including CO$_2$ emissions as negative capital. Through investments into climate change abatement and reduction of GHG emissions, consumption in the present is reduced in order mitigate economically negative effects of climate change in the future and therefore increasing consumption.
possibilities in the future. A schematic description of the model and interactions between different modules of the model can be seen in figure 2.1.

This way, the DICE model allows for a cost-benefit analysis which is used as a basis for decision making. The underlying question of the DICE model is how much should be invested for climate protection today (costs) in order to prevent costs by damages through climate change in the future (benefits).

The DICE model is doing the Cost-Benefit analysis by optimizing a welfare function taking consumption, emissions and climate change into account. Through establishing a relationship between economic damages and climate change driven by an increase of the $CO_2$ concentration in the atmosphere, every emitted ton of $CO_2$ can be assigned a certain cost. This cost is also described as Social Cost of Carbon (SCC) which has developed into an important concept in climate economics and policy making. Through SCC the costs of $CO_2$ emissions are internalized and similar mechanisms can be used by policy makers through carbon taxes or Cap-and-Trade systems.

### 2.2.2 Model Description

In the following the DICE model will be qualitatively described. The full set of equations as well as used parameters can be found in Appendix C, Section 7.3.

Generally speaking, the model can be subdivided into two modules: One module describing the economic development and another module describing geophysical relationships of climate change. The two modules are linked with each other, allowing for the integrated assessment. The two different modules as well as the containing variables are described in detail below.
2.2.2.1 Economic Module

The global net economic output ($Q(t)$) is defined as:

$$Q(t) = \Omega(t) \ast [1 - \Lambda(t)] Y(t)$$  \hspace{1cm} (1)

$Y(t)$ describes the gross economic output in form of a Douglas-Cobb production function, which makes the gross output dependent on labour ($L(t)$), capital ($K(t)$) and technological change ($A(t)$).

$$Y(t) = A(t) \ast L(t)^\alpha \ast K(t)^\beta$$  \hspace{1cm} (2)

$\Omega$ and $\Lambda$ - included in net economic output - describe the damage function and the costs of emission abatement respectively. The damage function is defined as:

$$\Omega(t) = 1 - D(t)$$  \hspace{1cm} (3)

with:

$$D(t) = \varphi_1 T_{AT}(t) + \varphi_2 T_{AT}^2$$  \hspace{1cm} (4)
D(t) therefore, describes the damages as a percentage loss of the gross economic output defined as GDP. The model assumes a quadratic relationship between damages and temperature changes. The change in temperature is an input from the geophysical module - as described below - and links the economic development to the geophysical development. However, several effects are not considered in detail within this damage function. These include among others: economic value losses from biodiversity, ocean acidification and changes in ocean circulations. Instead the damage function is adjusted with a 25% addition to the monetized damages in order to account for these effects. All these sectors will be reviewed with the current biophysical evidence in section 3. The factors $\varphi_1$ and $\varphi_2$ are used to control the form of the damage function and their values are chosen to fit the damage function to the respective evidence.

Abatement costs are defined as:

$$\Lambda(t) = \theta_1(t)\mu(t)^{\theta_2}$$  \hspace{1cm} (5)

where $\mu$ describes the emission reduction rate over time, $\theta_1$ and $\theta_2$ control the abatement cost function. $\theta_1$ describes the adjusted costs of backstop technology such as Carbon Capture and Storage (CCS) technology.

The total output $Q(t)$ is then divided into consumption and investment:

$$Q(t) = C(t) + I(t)$$  \hspace{1cm} (6)

The definition of per capita consumption follows as:

$$c(t) = \frac{C(t)}{L(t)}$$  \hspace{1cm} (7)

From the economic development the total emissions caused by industrial activity are derived:

$$E_{Ind} = \sigma(t)(1 - \mu(t))Y(t)$$  \hspace{1cm} (8)

The parameter $\sigma$ describes the carbon intensity per unit economic output as GDP while $\mu$ describes the emission reduction over time. Therefore, the total emissions
from industrial activity are dependent on the industrial activity itself (as gross output $Y(t)$), the emission intensity per economic output ($\sigma(t)$) and the reduction of emission intensity over time ($\mu(t)$).

2.2.2.2 Geophysical Module

The emissions from industrial activity are used as an input to the geophysical module where the total $CO_2$ emissions are calculated as:

$$E(t) = E_{Ind}(t) + E_{Land}(t)$$  \hspace{1cm} (9)

$E_{Land}$ describe the emissions as a result of change in land use and deforestation.

The carbon can be stored within three reservoirs relevant for the development of the world's climate: The atmosphere (AT), the upper oceans (UP) and the lower oceans (LO). Between those reservoirs, carbon is transported with different rates. The content per reservoir and the changes between reservoirs are then described as:

$$\begin{bmatrix} M_{AT} \\ M_{UP} \\ M_{LO} \end{bmatrix} = \begin{bmatrix} \phi_{11} & \phi_{21} & 0 \\ \phi_{21} & \phi_{22} & \phi_{32} \\ 0 & \phi_{32} & \phi_{33} \end{bmatrix} \times \begin{bmatrix} M_{AT}(t-1) \\ M_{UP}(t-1) \\ M_{LO}(t-1) \end{bmatrix} + \begin{bmatrix} E \\ 0 \\ 0 \end{bmatrix}$$  \hspace{1cm} (10)

The flow between reservoirs is described with $\phi_{ij}$ while it is assumed that all emissions initially flow into the atmosphere. Based on the $CO_2$ content in the atmosphere the radiative forcing from $CO_2$ relative to the pre-industrial level can be calculated:

$$F(t) = \eta \{ \log_2 \frac{M_{AT}(t)}{M_{AT1750}} \} + F_{ex}(t)$$  \hspace{1cm} (11)

$F_{ex}(t)$ denotes exogenous radiative forcing from other sources such as other greenhouse gases, aerosols, ozone or the albedo effect. $\eta$ describes the climate sensitivity as the forcing due to a doubling in $CO_2$ concentrations.

Based on the radiative forcing the temperature change in the atmosphere can be
calculated as:

\[ T_{AT}(t) = T_{AT}(t-1) + \zeta_1 \{ F(t) - \zeta_2 T_{AT}(t-1) - \zeta_3 [T_{AT}(t-1) - T_{LO}(t-1)] \} \]  

(12)

The term for the lower oceans considers the inertia of the system. This temperature can be defined as:

\[ T_{LO}(t) = T_{LO}(t-1) + \zeta_4 \{ T_{AT}(t-1) - T_{LO}(t-1) \} \]

(13)

2.2.2.3 Optimization Function  The model is solved in order to maximize the welfare function given as:

\[ W = \sum_{t=1}^{T} U[c(t)]L(t)R(t) \]

(14)

The welfare function sums up utility over time, which is dependent on the utility function (and therefore on per capita consumption), population and a discount rate \( R(t) \). The model solver aims at maximizing the overall welfare for the total given timeframe, which is 500 years in the given model. The utility function is defined as:

\[ U(t) = \frac{c^{(1-\alpha)}}{1-\alpha} \]

(15)

The coefficient \( \alpha \) measures the relative importance of consumption at different points in time and can be understood as a measure for inequality aversion with \( \alpha \to 1 \) high inequality aversion and \( \alpha \to 0 \) low inequality aversion. Similarly, the discount rate \( R(t) \) is defined as:

\[ R(t) = (1 + \rho)^{-t} \]

(16)

where \( \rho \) describes the generational discount rate on welfare.
2.2.3 Criticism

The results obtained from the model as well as the methodology of IAMs is often debated controversially in literature.

As a result of his analysis Nordhaus argued that with recent developments in climate policy and the little efforts for reducing GHG emissions before 2017, climate goals such as the Paris agreement are economically suboptimal or even unattainable. In order to keep global warming below 2°C or even 1.5°C the measures to reduce emissions would need to be so drastic and costly that they would outweigh the benefits from prevented climate change damages in the future. Instead Nordhaus suggested to aim for a target of 3°C global warming by 2100, which is much closer to the optimal run of his version of the DICE model (W. Nordhaus 2019).

The popularity of IAMs and their use by policymakers such as EPA in the U.S. as well as the IPCC has raised the question how reliable IAMs are and how well they are suited for policy making.

One of the most prominent critiques, Robert Pindyck, argues that IAMs are very sensitive to certain inputs such as the equilibrium climate sensitivity, the discount rate, treatment of catastrophic outcomes as well as the damage function (Pindyck 2013). Changes in these inputs can influence outcomes of the IAMs such as the SCC by several orders of magnitude. At the same time these inputs are subject to great uncertainty. Since the damage function and chosen discount rate often lack a foundation of data or scientific knowledge Pindyck argues that they can be chosen arbitrarily. He therefore limits the value of IAMs to educational value in order to illustrate the relations between different factors in climate change economics (Pindyck 2017). Furthermore, according to Pindyck the uncertainty in inputs and lack of consensus, theory, and data could also make the models prone to bias since inputs could be changed in order to achieve certain desired outcomes.

Pindyck states that the use of these models overall suggest a level of knowledge which is non-existent. Additionally, other factors such as the tail risk of catastrophic outcomes could be factors that drive the price of SCC which are so far not sufficiently considered in IAMs (Pindyck 2019).

On the other side Metcalf and Stock (2015) argue that IAMs are structurally correct
and therefore helped to identify key research areas such as climate damages in order to increase certainty of IAMs and decrease the width of outcomes.

Similarly, Hänsel et al. (2020) used the model of Nordhaus in order to show that inputs that are updated to recent developments in climate science and economics can lead to results that put the outcomes of the DICE model in line with the goals set out in the Paris Agreement. In their update the structure of the model was not changed while only inputs to certain areas of the model such as the climate model, the damage function and the discount rate were updated.

In the following, this thesis will make a first attempt at filling knowledge gaps included in the DICE model. As done in Hänsel et al. (2020) and Metcalf and Stock (2015), a bottom up approach will be investigated were single sectors and the respective damage due to climate change will be investigated. Large advancements within biophysical models help to support the estimates of damages with a scientific data foundation that helps in reducing uncertainties related to damages and offers high transparency which allows for further future updates along scientific improvements. More specifically, this thesis will investigate the damages related to the ocean and its ecosystems and put those damages in context to the assumptions taken in the DICE model.

### 2.3 The Damage Function

The damage function is a crucial concept within IAMs and model outcomes are often highly sensitive to assumed forms of the damage function. There are different methodologies used for the estimation of damage functions namely: biophysical process models, structural economic models and statistical models (Bednar-Friedl et al. 2022).

- **Biophysical process models:** These models are based on processes observed in natural sciences and system responses to climate change. For damage estimations with these models the total damage response is usually derived by summing up the responses from several economically relevant sectors such as agriculture, forestry, human health, coastal development etc. All sectors and their response to climate change are modelled individually and the damage relative to an increase in atmospheric temperature is combined into one total
damage function. The advantage of biophysical process models is that they offer greater transparency on which damages are included and excluded which makes them easier to interpret. However, they can be computationally very intense and interactions between sectors are difficult to model.

- **Structural economic models:** These models are capable of simulating the impacts from climate change on production, household consumption and market inputs using computable general equilibrium models (CGEs). CGE models use actual economic data to derive a model which is calibrated to this benchmark of actual economic data. Through variation in the model, different policies or impacts such as shocks and their effect on the economy or agents within the economy can be studied. CGEs take interdependencies between sectors and markets into consideration which allows for a wider economic evaluation (Government 2016)

- **Statistical models:** Statistical models infer impacts from climate change through analysis of changes in weather and economic factors and the response in the economy to these changes.

Apart from these distinct methodologies, hybrid methodologies or aggregations of data through meta-analysis is also an often used option. Meta analysis are used to review several different studies with the same research goal and perform statistical analysis in order to account for an assumed degree of error in the results of the individual studies.

Throughout the development of the DICE model the methodology for deriving the damage function has changed. While the first studies used methodologies closer to biophysical process models, where selected sectors were modelled, from 2013 and onwards Nordhaus carried out meta-analysis instead. In the first estimations for the damage function of the DICE model damages in agriculture, energy demand and sea level rise were estimated using data from the US. Since data availability was missing at the time for the rest of the world, this data was extrapolated to other countries using proxies such as coast line length. This estimation was later refined with more available data and further sectors such as health, human settlements and non-market amenities were included. Furthermore, the effect of catastrophic outcomes was first considered within the damage function. Throughout the further
development of the DICE model these assessments were updated while the general structure remained the same.

The damage function for the 2013 model was based on a meta-analysis developed by R. S. J. Tol (2009) which also serves as basis for another IAM - the FUND model. The analysis done by R. S. J. Tol (2009) was later criticised for containing numerous statistical errors. A following correction was later published and further criticised for containing errors (R. S. Tol 2014). Given the errors in the latest version of the DICE model, Nordhaus developed his own meta-analysis which serves as a basis for the damage function in the DICE2016R2 model (W. D. Nordhaus 2017).

The meta-analysis conducted for the DICE2016R2 version resembles the one done by R. S. Tol (2014) since selected studies are to a large extend based on studies contained in the R. S. Tol (2014) study and further extended by Nordhaus through systematic and non-systematic research studies (W. D. Nordhaus 2017).

The use of meta-analysis as methodology for the derivation of the damage function comes with several complications. Since a meta-analysis takes numerous other studies containing estimates for global aggregate damages as inputs, the results are less traceable. Therefore, it is more difficult to analyse which impacts from climate change are exactly excluded in the damage function (P. Howard 2014). Nordhaus concludes that the analysis for the DICE2013 as well as DICE2016R2 version omits damages related to value loss due to decreased biodiversity, ocean acidification, extreme sea-level rise, changes in ocean circulation, accelerated climate change as well as uncertainty and catastrophic events. In order to compensate for these effects a 25% addition to the monetized damages is added to the function.

Additionally, the derivation of the damage functions contained in the DICE model has been criticised for citation bias and circular referencing (Pindyck 2013; P. H. Howard and Sterner 2017) where predictions of damage functions are often based on the estimates of earlier versions of the same model. This could be one reason why there has been very little change in the magnitude of the damage function over time in the DICE model as seen in figure 2.2.

The different damage functions that have been used over time in the different versions of the DICE model as well as a comparison with the damage function
used by Hänsel et al. (2020) is shown in figure 2.2. It can be seen that there have been little changes over time.

![Figure 2.2: Historic development of the damage function in the DICE model.](image)

In their update of the DICE model Hänsel et al. (2020) keep the structure of the damage function the same as in the original DICE2016R2 version with damages assumed to follow the form of a quadratic function. In order to derive the factors $\varphi_1$ and $\varphi_2$ of the damage function - and therefore determining the magnitude of damages - they apply the meta analysis by P. H. Howard and Sterner (2017) in which only estimations from most recent model calculations are included and therefore avoiding the inclusion of duplicate estimates. With the updated damage function and the DICE2013 model P. H. Howard and Sterner (2017) found that the prize for SCC would increase four to fivefold. Similarly, Hänsel et al. (2020) found that the change in damage function in the 2016R2 model lead to a significant reduction of the desirable temperature increase by 2100. However, it is still acknowledged that this damage estimate is rather conservative compared to more recent micro-econometric studies and expert elicitations by P. H. Howard and Sylvan (2015) and Pindyck (2019). Furthermore, non-market goods are still excluded in the estimate with specifically biodiversity and loss of coral reefs being mentioned to have potentially significant effects on the outcome of the estimate (Hänsel et al. 2020).
2.4 Incorporating the value of nature and ecosystem services

The DICE model is structured in a way which aims at optimizing the welfare function over time. Welfare is essentially defined as consumption per capita - ergo high consumption possibilities are regarded as high welfare. The definition of the welfare function as implemented in the DICE model considers welfare based on the development of Gross Domestic Product (GDP) and therefore only based on the consumption of market goods such as food, cars and travel. GDP generally considers the monetary value of market goods and services at the final stage of consumption for a certain time period (Fund 2023).

Using GDP as a sole indicator for welfare has often been criticised for ignoring important aspects such as the contributions from nature and ecosystem services to the economy and the value of nature for human well-being (Dasgupta 2021; J. Boyd and Banzhaf 2007; Costanza, Hart, et al. 2009). However, methodologies for valuing ecosystem services and their use and incorporation into market systems has been widely discussed but to date there is no commonly used and widely accepted framework readily available to be put into practice.

One of the first attempts to bring the value of nature and ecosystem services to public attention was made by Costanza, d’Arge, et al. (1997) who aimed at estimating the value of global ecosystems. At the time the value of the global biosphere was estimated at an average of 33 trillion USD. In later updates the value was increased to around 125 trillion USD (Costanza, De Groot, et al. 2014) and 150 trillion (Li and Fang 2014) which in all cases constitutes more then the economic output at the time. Hereby, the vast majority of value from ecosystem services is supplied by marine ecosystems which account for around 75% of all ecosystem service value and therefore showcase a significant role in supporting and sustaining our society and global ecosystems (Li and Fang 2014).

In order to properly account for damages to ecosystems and their services as well as their contribution to national accounting, two main approaches have been developed so far.

The first approach as currently used in IAMs and presented in section 2.2.2 is the
use of a damage function. The use of the damage function solves issues regarding externalities from harmful economic activities and therefore addresses one important market failure. However, as previously discussed damage functions so far only consider damages to marketed goods and therefore ignore the value and damages to ecosystem services which are outside of the market.

Contrasting to the damage function currently implemented in any version of the DICE model, damages to regulating and maintenance services of ecosystems will be included in the here implemented damage function. The current damage functions measure damages from emitted emissions against economic output in the form of GDP which does not include regulating and maintenance ecosystem services. However, since these will be included in the damage function, they also need to be included in the measure of economic output in order to allow for a consistent assessment.

\[
\text{loss of GDP in } [\%] = \frac{\text{market losses} + \text{biosphere losses}}{\text{market output} + \text{biosphere output}} \quad (17)
\]

A methodological approach for this extension is presented in Dasgupta (2021) where the value of ecosystem services is included into the production function and therefore the total economic output. This approach will be further described below.

### 2.4.1 The production function and ecosystem services

As a starting point the Cobb-Douglas production function is considered, which is also used for computing the economic output within the DICE model:

\[
Y = A \cdot L^\alpha \cdot K^\gamma \quad (18)
\]

where \( L \) represents human capital or labour, \( K \) represents capital stocks and \( A \) the Total Factor Productivity (TFP). TFP essentially reflects the state of knowledge, technology and institutions allowing for more efficient combinations and use of \( K \) and \( L \) (Döhring et al. 2023).

The exponents \( \alpha \) and \( \gamma \) represent the output elasticities. These describe to which extend the total output increases if one of the inputs into the production function
is increased (e.g. if \( \gamma = 0.3 \) then 1% increase in capital stocks results in a 0.3% increase in total output). Through output elasticities the substitutienality between goods is described, therefore how well can capital be replaced by human capital while maintaining the same output or vice versa. For the purpose of this model the sum of the output elasticities is considered to be equal to 1:

\[
\alpha + \gamma = 1
\]  

(19)

This relationship is also described as constant returns to scale meaning that doubling the value of capital as well as human capital will result in a doubling of the total economic output.

In a next step the production function is extended by a factor \( R \) which describes natural capital stocks which have direct provisioning services such as fish, timber etc. Since these provisioning service are a direct flow into the economy, they are already considered in current economic output functions. The explicit distinction between capital and natural stocks therefore does not change any dynamics in the economic model, it serves more the explicit distinction between natural capital and other capital. The production function is then written as:

\[
Y = A \cdot L^\alpha \cdot K^{\gamma} \cdot R^{(1-\alpha-\gamma)}
\]  

(20)

The output elasticities in this production function still sum to 1 reflecting constant scale of returns. In other cases, if the output elasticities would be below 1 this would mean that each input is essential and full substitution is not possible between production factors. Considering constant productivity and labour this would mean that natural capital is considered as an essential input which is not fully substitutional and therefore the depletion of this stock will eventually lead to a collapse of the economy.

The opposite is the case if elasticities sum up to a value above 1 meaning that each input is perfectly substitutable and a depletion of one can be compensated and substituted by another input.

While human capital can be regarded as constant over time with a stagnating
population size of around 11 billion - as modelled in the DICE model according to projections from the UN - productivity and capital should not be considered as constant. In the DICE model their development over time is modelled as:

\[ K(t) = (1 - dk)^t \cdot K(t-1) + t \cdot I(t) \]  

(21)

with \( dk \) describing the depreciation rate of capital and \( I(t) \) describing the rate of investments into capital.

TFP (A) is described as:

\[ A(t) = \frac{A(t-1)}{1 - ga(t)} \]  

(22)

with \( ga(t) \) being the growth rate of TFP:

\[ ga(t) = ga_0 \cdot e^{-d \cdot t_{step}} \]  

(23)

The growth rate is assumed to decline over time with the factor \( d \) and the time interval of five years \( (t_{step}) \) in the exponent.

In a third step ecosystems services that reflect maintenance and regulating services are included in the production function through the factor \( S^\beta \).

The combined factor of \( AS^\beta \) then reflects the state of knowledge and institutions as well as the state of the biosphere. This specifically considers ecosystem services such as maintenance, restoration and regulation services which are needed for a productive biosphere.

In the model developed by Dasgupta (2021) the biosphere is affected by extraction and depletion of resources as well as waste related to economic activities which is released into the environment. The effect on the biosphere \( (S(t)) \) and its regenerative capacities \( (G[S(t)]) \) over time by extraction of resources and the input of waste are described as:

\[ \frac{\partial S(t)}{\partial t} = G(S(t)) - R(t) - w(t) \]  

(24)
where $R(t)$ describes the provisioning services from the biosphere which are directly extracted (e.g. fish, timber etc.) and $w(t)$ describes the flow of waste that degrades the biosphere.

In the DICE model a very special case of waste in the form of $CO_2$ emissions is considered while other effects on the biosphere from extraction and land use change will be disregarded. In the here developed model the change of the biosphere $\frac{\partial S(t)}{\partial t}$ is considered to be modelled through the damage function.

In order to account for damages to ecosystem services and natural capital in a consistent manner the model presented in 2.2.2 will be adjusted according to the model presented in Dasgupta (2021). Dasgupta (2021) presented in his review a detailed assessment of the significance of biodiversity and nature for society and advocates for a paradigm change in which the human system is no longer regarded separate from the human world but rather a human society which is founded on or embedded in nature.

In order to properly account for ecosystem services and their significance for the economy the definition of total output in the economy will be extended - including natural capital and services.

Within the scope of this model $S^\beta$ is assumed to be constant over time in a sense that there is a maximum amount of maintenance and regulative services that can be provided by the biosphere similarly to human population being constant for long time horizons.

This is a first crude assumption on the way of implementing the value of the biosphere into damages and economic output estimation. Costanza, De Groot, et al. (2014) have shown that the value of ecosystem services change over time. However, modelling the possible changes in ecosystem service value over time and included drivers - which go beyond the impact of climate change - is out of the scope of this thesis. The significance of this development is however acknowledged.

It should be noted that there is to date no specific implementation of Dasgupta’s model available which would give suggestions for precise numbers taken for the factor $S^\beta$. For now the value $S$ is taken as the global biosphere value from De Groot et al. (2012) while the exponent $\beta$ - which denotes the flow of the value of
the biosphere into the economy - is assumed with 0.2 for a first estimation. The importance and sensitivity of the model to these assumptions is acknowledged and further research is needed to make the model fit for practical purposes. However, for first demonstrations of the model within the scope of this thesis, these assumptions are taken to be sufficient.

The results of the changes in the economic model are shown in appendix A. It can be observed that there are no structural differences in the behavior of the model no matter whether ecosystem services are included in the economic output model or not. The optimal temperature increase estimated by the model remains around 4 and the SCC peaks around 2,200 USD/t CO2 in both models. Abatement costs and economic output behave structurally similar with different magnitudes which is explained by the inclusion of ecosystem services and a higher total output.

Since damages are calculated as percent of the total output their absolute value is increased connected to the higher gross output value leading to an earlier peak in SCC.

After changing the economic output model the changes on the damage function and impacts of these changes on the model output will be described and discussed below.
3 Impact Assessment

In order to assess the impacts from climate change on the different sectors a two step process is established to determine impacts and damages. In a first step (i) an impact assessment is done through literature review and application of developed models for climate change impacts. For the economic valuation of the impacts (ii) different methodologies are applied depending on the context of the valuation (ecosystem services, direct use values etc.)

3.1 Coral Reefs

Coral reefs cover a relatively small part of the ocean, however, they contain over 25% of the marine biodiversity making them one of the most biodiversity rich biomes on the planet. Reefs also provide the human society with important ecosystem services such as provisioning of food and genetic resources, protection from erosion and extreme event mitigation as well as value for recreation and tourism (Chen et al. 2015; Hoegh-Guldberg, Mumby, et al. 2007).

However, in the past a significant loss in coral cover could be observed as a result of different stressors. These include non-climate stressors such as pollution, destructive fishing techniques, overfishing as well as coastal development. Next to these, climate drivers such as warming of the Sea Surface Temperature (SST) as well as ocean acidification have had significant impacts, especially on tropical warm water reefs (Bednar-Friedl et al. 2022; Hoegh-Guldberg 1999; Hughes et al. 2017; Souter et al. 2020).

Through the warming of the ocean surface and the increased appearance of Marine Heat Waves (MHWs) coral reefs are exposed to environmental conditions which are beyond their thermal tolerance. The exposure to high temperatures as well as intense solar radiation result in complications during the photosynthesis process of small symbiotic algae within the coral tissue, eventually leading to the loss of the algae and the death of the corals. These phenomena are also described as bleaching events and their correlation to increased sea temperature is well established (Frieler et al. 2013; Hoegh-Guldberg, Mumby, et al. 2007).

Marine heat waves where the long term maximum sea surface temperature is
increased by 1°C for about 4 to 6 weeks are enough to cause significant damages with losses up to 85% reported for bleaching events in 2016 (Hoegh-Guldberg, Jacob, et al. 2018; Hughes et al. 2017). The increased probability of environmental conditions which result in bleaching events was already predicted in the late 90s by Hoegh-Guldberg (1999) and predictions of corals facing bleaching events in back to back years have become reality in the period between 2016 and 2017 (Pratchett et al. 2021).

According to the IPCC assessment coral reefs are already close to their thermal thresholds. The impacts from climate change and the risk which climate change poses has become particularly visible in recent years. While approximately 50% of the global reefs have been lost over the last 30 years, large reef systems - such as the great barrier reef for instance - also have experienced substantial losses during the period of 2016-2018 where half of the shallow water corals have been lost in only 3 years (Hoegh-Guldberg, Jacob, et al. 2018).

In addition to heat stress, coral reefs are experiencing additional pressure through ocean acidification as a result of increasing CO₂ concentrations in the atmosphere. Dissolved CO₂ results in binding of carbonate ions which reduces the availability of carbonate needed in the calcification process of corals. As a result, reduced growth rates for corals and net erosion of coral reefs can be observed.

When projecting the damages from climate change several factors such as adaptation and possible mitigation measures need to be considered. However, the measures for mitigation for coral reef loss are very limited. While Marine Protected Areas (MPAs) can help to reduce the stress on corals from non-climate stressors, their effectiveness to limit damage from climate change is not significant (Hughes et al. 2017; Pandolfi et al. 2011). Mitigation measures such as restoration and management are assumed to lose effectiveness beyond warming of 2°C while measures such as coral and reef shading will lose their effectiveness beyond 3°C warming (Bednar-Friedl et al. 2022).

For the evaluation of the impacts from climate change on coral reefs, several studies from Frieler et al. (2013), S. D. Donner (2009) and studies included in the 6th IPCC Assessment Report (Hoegh-Guldberg, Jacob, et al. 2018) are reviewed. Frieler et al. (2013) provide scenario independent projections for coral cover loss as response
to global warming using Degree Heating Months (DHMs). These describe the accumulated time and intensity at which the SST exceeds the mean of maximum monthly temperatures measured during a time period before the year 2000. It is assumed that 2° C x month is the upper threshold at which bleaching occurs.

In their studies, Hoegh-Guldberg, Jacob, et al. (2018) and Frieler et al. (2013) include estimates of adaption rates of 0.2-1.0°C per decade as a result of more resistant symbionts. Furthermore, a recovery rate of about 5 years is assumed as a threshold meaning that permanent reef degradation can be expected when bleaching events occur more frequently than every five years. These estimates are considered to be very optimistic since adaptation rates of this magnitude have not been observed yet and recovery rates tend to be rather > 15 years (Bednar-Friedl et al. 2022).

Additionally, a sensitivity analysis has been carried out including the impacts of ocean acidification on the thermal tolerance of coral reefs. In their study Frieler et al. (2013) assume that bleaching thresholds decrease linearly with decreased aragonite satiration as a result of decreased ocean pH from 2 ° C x month to 0 ° C x month. Similar observations have been made with pollution increasing the severity of bleaching events. The results show that acidification has no significant impact on the percentage of reef cells at risk for bleaching since the thermal threshold of 2 °C is already exceeded for most reef cells before acidification becomes relevant. However, the added pressure from ocean acidification might lead to earlier and more severe bleaching events when considered in time dependent models.

Their results show that global warming would need to be limited to 1.2 ± 0.2 °C in order to limit the loss in coral cover to about 50%. At an increase of 1.5°C above pre industrial levels losses could be up to 85% ±15 while an increase of 2°C would result in a loss of virtually all coral reefs.

In another study, S. D. Donner (2009) comes to very similar conclusions and shows that the already emitted CO₂ emissions up until the year 2000 and the related time lack in climate response could result in coral loss of 50% until 2080 and find agreeing results with losses of >99% of coral cover by mid century even in low emission scenarios.

In figure 3.1 the relationship between temperature change and coral loss from Frieler...
et al. (2013) as well as from Bednar-Friedl et al. (2022) are shown. The two estimates are used as inputs for the description of coral loss which is further used in this analysis and shown as "Estimate" in figure 3.1.

![Figure 3.1: Predicted Coral loss per temperature change](image)

**3.2 Fisheries**

The fishing sector is supporting a significant amount of people with food and livelihoods. On average 17% of animal protein is supplied by marine food and the fishing sector provides jobs and income for about 600 million people who at least partially depend on fisheries (FAO 2022). Fishing is a particularly important sector to many low income countries and especially to coastal states in the tropics (Thiault et al. 2019; Lam et al. 2016).

With an increasing world population the amount of produced seafood has dramatically increased over the past years with yearly annual production capacity of around 214 million tons in 2020 compared to around 75 million tons in 1980, where the production of seafood is outpacing population growth resulting in increasing per capita seafood consumption (FAO 2022). The majority of the uptake in production capacity has been carried by the uptake of aquacultures with limited opportunities for growth in capture fisheries, which are fishing the majority of global fish stocks at the maximum sustainable yield or above.

With changing environmental conditions in the ocean as an effect of climate change,
capture fisheries and aquacultures face several challenges ahead. On a global scale the development of aquacultures in the future is rather indifferent. While through warming waters the global suitable area for finfish cultures could expand, shellfish cultures face severe challenges and risks as a result of ocean acidification. Narita, Rehdanz, and R. S. Tol (2012) for instance estimate that the impacts of ocean acidification on the US mollusk cultures could result in economic losses of up to 100 billion USD worldwide depending on the assessed scenario. Furthermore, aquacultures are vulnerable to secondary effects of global warming such as storms, floods and changes in precipitation (Barange et al. 2018).

The development of future catch potential for capture fisheries is influenced by three main drivers: (i) fish physiology, (ii) food availability and (iii) habitat suitability (W. Cheung 2018).

For the estimation of fisheries development under climate change different models can be used. Dynamic Bioclimate Envelope Models (DBEM) simulate species interactions and ocean conditions by modelling the changing environmental conditions and linking them to factors such as habitat productivity and suitability, ecophysiology and population dynamics (W. W. L. Cheung et al. 2016). Alternatively, Living Resource Models can be used, which couple the development of geophysical water properties such as water temperature, oxygen concentration and pH value with projections on future changes in biomass of upper trophic consumers or economically exploited fish stocks based on the change in net primary production and effects on the whole food web. Net primary production describes the ability of marine ecosystems to fixate CO₂ and supplying organic matter and energy and therefore supporting marine food webs (Tagliaabue et al. 2021).

The warming of the oceans generally results in poleward species shift where the observed shift of species in the marine environment is much faster compared to terrestrial species despite the slower warming of the oceans compared to land. As a result, especially the tropics experience a loss of species, with more species leaving the tropics than entering them. This leads to a high variability in impacts on fish stocks globally, where a decrease of fish availability of over 40% is projected for the tropics and the South Pacific in particular. An opposite effect can be observed in the arctic Pacific, which could experience an increase of up to 30% (Barange et al. 2018).
The increase in catch potential in these regions is mainly driven by an increased habitat suitability due to increased water temperatures for species from lower altitudes and as well increased habitat sizes with decreasing sea ice.

The development of fish stocks is further influenced through the warming induced increase in stratification of the oceans. Ocean stratification describes the effect where the water column is separated into different layers due to changing water density with changing temperature. The decrease in mixing between different layers in the water column leads to less nutrient rich water reaching the top layer and oxygen rich water reaching the bottom layer. This affects the productivity of phytoplankton and small algae in the upper layer which are then limited by nutrient availability (W. Cheung 2018). This reduction is further amplified towards higher trophic layers - such as fish - with an average decrease in total marine biomass of around 5% per degree warming (Lotze et al. 2019).

The heterogeneity in development of maximum catch potential poses particular problems to small coastal states in the tropics. Especially countries that score low in the Human Development Index (HDI) and that are low income and food deficit countries often depend largely on fish as nutritional source and source for income. At the same time the affected communities in the tropics are often the most dependent on fisheries, where this sector forms a main economic sector and serves as a foundation of the national economy. These circumstances often leave these countries with the least capacity for adaptation such as diversification, while they face additional pressure from climate induced losses in terrestrial agriculture (Thiault et al. 2019). These potentially catastrophic outcomes for affected countries will likely lead to secondary effects and additional damages such as social conflicts, migration and poverty which are not included in the damage assessment presented in this thesis.
Figure 3.2: Projections for productivity, sensitivity and adaptation capacity for fisheries worldwide under IPCC climate scenario RCP8.5 (Thiault et al. 2019).

For estimating the change in fisheries production, the models for the development of fisheries under climate change from W. Cheung (2018), Lam et al. (2016) and W. W. Cheung, Reygondeau, and Frölicher (2016) are used.

The agreement between models on large scale trends in the development of fishery catches is high. They find that global fisheries production is expected to decrease by 5.3% to 7% by 2050 while the global revenue is projected to decrease by 10.4% in 2050. The over proportional decrease in revenue is a result of a decrease in catch of especially economically valuable fish species.

The results found in W. W. L. Cheung et al. (2016), W. Cheung (2018), Lam et al. (2016) as well as the estimate which is further used in this analysis are shown in 3.3.
3.3 Mangrove Forests & Sea Grass Meadows

Mangrove forests and seagrass meadows represent important ecosystems that provide our society with a range of ecosystem services such as coastal protection, erosion prevention, regulating services and are habitat and breeding ground for many fish species which benefits the fishing industry. However, there has been a significant decline in these ecosystems which was mainly driven by coastal development and is now amplified through effects from climate change. Sea grass meadows experienced a decline of around 29% compared to pre-industrial levels, while losses in mangrove forests are estimated at 0.16%- 2% per year on average for the period between 2000 and 2010 which could result in a total loss of mangrove forests within this century (Cooley et al. 2022; Alongi 2015).

While the decline in the past has been mainly driven by water quality degradation, urban development and deforestation (e.g. for aquacultures), extreme weather events such as marine heatwaves, floods and droughts in the recent past caused mass mortalities among mangroves and seagrass meadows which amplifies the risk for phase shifts of the biomes resulting in alternative states of the ecosystems and changes in species composition (Duke et al. 2021; Serrano et al. 2021).

For seagrass meadows sea temperature increases beyond their thermal tolerance are expected to be the driving factor in climate induced decline (Serrano et al. 2021).
However, some evidence suggests, that thermal tolerance for some species is raised through ocean acidification and increased photosynthesis activity (Zimmerman 2021; Garrard and Beaumont 2014).

Among different effects related to climate change, sea-level rise is considered to be the most concerning effect for mangrove forests (Alongi 2015). According to the most recent IPCC assessment report mangrove forests are projected to decline under all emission scenarios with increasing severity by mid century (Cooley et al. 2022). Hereby, nature based solutions are projected to be insufficient to protect mangroves beyond the 2040’s. An inclusive management approach, reducing the pressure from non-climate stressors would help to reduce the decline in mangrove forests and seagrass meadows and could support in increasing the tolerance for climate induced pressure. Mangroves do have the capacity to expand vertically by building up seafloor through sedimentation and to migrate landwards with rising sea levels. However, the capacity for migration is very site specific and depends on local circumstances such as topography and coastal development. Furthermore, some species could migrate polewards under global warming, which could result in net benefits for some regions.

Literature on global projections for the development of mangroves as well as seagrass meadows is scarce and future developments are very site specific and largely depending on management and changes from non-climate stressors. Furthermore, different environmental changes from climate change such as temperature increase and ocean acidification can have counteracting effects, making the biophysical evidence on the development of seagrass meadows and mangrove forests under climate change rather inconclusive. For this reason mangrove forests and seagrass meadows are not further included in the model. Future evidence, that gives a clearer indication on the development of the biomes under climate change could be incorporated into the model as part of future research.
4 Economic Valuation & Damages

The results from the impact assessment - as presented in section 3 - are further used in this section to monetize the damages in order to make them usable within the DICE model.

4.1 Coral Reefs

The valuation for coral reefs is done following the methodology similar as described in De Groot et al. (2012), who reviewed data for different biomes including open oceans, coral reefs, coastal systems, temperate and tropical forests as well as wetlands. Through the review of side specific valuations, average data for ecosystems per area in standardized monetary units is derived and fed into the Ecosystem Service Value Database (ESVD). The ESVD contains over 6,000 studies for local case studies evaluating ecosystem value ranging across 10 different biomes and 22 ecosystem services. The most recent data contained in the ESVD is used in this thesis to derive average values for coral reefs (ESVD 2022). The number of studies found in the ESVD per topic is shown in table 4.1.

The used values for this study are standardized to Int\$ Per Hectare Per Year as 2020 value. The data is analyzed separately for different ecosystem services per biome, where the ecosystem services with sufficient data availability (>10 studies) are selected. For coral reefs this includes tourism, food provisioning, erosion prevention as well as moderation of extreme events.

For the estimation of value in monetary units a range of estimation methods are included. The most commonly used methods vary depending on the evaluated ecosystem service. Applied methods include market price valuation, replacement cost, stated and revealed preference as well as travel costs.
Table 4.1: Available studies by ecosystem service for coral reefs.

<table>
<thead>
<tr>
<th>Ecosystem Service</th>
<th>No of available studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesthetic Information</td>
<td>3</td>
</tr>
<tr>
<td>Climate Regulation</td>
<td>1</td>
</tr>
<tr>
<td>Erosion Prevention</td>
<td>12</td>
</tr>
<tr>
<td>Existance, Bequest Value</td>
<td>39</td>
</tr>
<tr>
<td>Food</td>
<td>56</td>
</tr>
<tr>
<td>Genetic Resources</td>
<td>1</td>
</tr>
<tr>
<td>Information for Cognitive Development</td>
<td>7</td>
</tr>
<tr>
<td>Inspiration for Art, Culture and Design</td>
<td>1</td>
</tr>
<tr>
<td>Maintenance of Genetic Diversity</td>
<td>1</td>
</tr>
<tr>
<td>Maintenance of Life Cycles</td>
<td>1</td>
</tr>
<tr>
<td>Medicinal Resources</td>
<td>1</td>
</tr>
<tr>
<td>Moderation of Extreme Events</td>
<td>10</td>
</tr>
<tr>
<td>Opportunities for Recreation and Tourism</td>
<td>149</td>
</tr>
<tr>
<td>Waste Treatment</td>
<td>1</td>
</tr>
</tbody>
</table>

The available data sets that contained the relevant ecosystem, ecosystem service and the necessary data for a standardized monetary value estimation were furthermore screened for obvious outliers which were then excluded from the evaluation. For this purpose the 95th percentile of studies is included in the analysis. With this method 95 studies for 4 ecosystem services were selected. Through the calculation of summarizing statistics (average, median, min, max and standard deviation) an overview over the value per ecosystem as well as over the distribution of estimations is given.

For the analysis of damages due to ecosystem loss, the mean values per ecosystem service for each biome are added up resulting in an total mean value per biome. The results for coral reefs are presented in table 4.2.

Table 4.2: Economic valuation of coral reefs in Int $ 2020 per ha per year.

<table>
<thead>
<tr>
<th>Coral Reefs</th>
<th>No. of Studies</th>
<th>Average</th>
<th>Min</th>
<th>Max</th>
<th>Median</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food</td>
<td>42</td>
<td>38,672</td>
<td>1</td>
<td>321,182</td>
<td>12,274</td>
<td>63,444</td>
</tr>
<tr>
<td>Toursim &amp; Recreation</td>
<td>84</td>
<td>285,160</td>
<td>7</td>
<td>1,546,183</td>
<td>63,434</td>
<td>400,050</td>
</tr>
<tr>
<td>Erosion Prevention</td>
<td>6</td>
<td>12,468</td>
<td>299</td>
<td>24,908</td>
<td>9,162</td>
<td>10,515</td>
</tr>
<tr>
<td>Moderation of Extreme Events</td>
<td>5</td>
<td>170,892</td>
<td>1,385</td>
<td>374,712</td>
<td>102,886</td>
<td>158,301</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>95</strong></td>
<td><strong>468,519</strong></td>
<td><strong>1,691</strong></td>
<td><strong>1,945,803</strong></td>
<td><strong>175,482</strong></td>
<td><strong>-</strong></td>
</tr>
</tbody>
</table>
Compared to the values found in De Groot et al. (2012) the total average value is increased from 352,915 $ha^{-1}year^{-1}$ to 468,519 $ha^{-1}year^{-1}$ which is an increase of around 30% while the number of included studies has been more than doubled.

The large spread in value characterizes the different properties of different ecosystem sites. For instance is the value of smaller and remote reefs for tourism much lower compared to large and heavily visited reefs. De Groot et al. (2012) state that their estimation is most likely a heavy underestimate of the real value considering that for each biome only a few of the 22 total ecosystem services were valued. The same is valid for this analysis, however, it is assumed that the services covering the major value of coral reefs are included within this analysis and therefore representing a good estimate of the value.

Considering these values the total economic benefit from coral reefs can be calculated. The worldwide coral reef coverage ($A_0$) is estimated around 259,000 $km^2$ which would result in a yearly benefit of:

$$\text{Output} = A_0 \cdot V_0 = 25.9 \cdot 10^6 ha \cdot 468.519 \frac{Int\$2020}{year \cdot ha}$$

This results in a benefit of around 12 trillion $ per year from coral reefs alone. Similar studies find values in the same order of magnitude (Rivera, Chan, and Luu 2020: 11 trillion; Costanza, de Groot, et al. 2014: 9.9 trillion) while other studies find slightly lower results (Souter et al. 2020: 2.7 trillion). In respect to these estimates the presented value represents rather the upper end of estimates. Considering possible omitted services and values as discussed in De Groot et al. (2012) a higher value might reflect the actual value of coral reefs closer to reality.

Similarly to W. Nordhaus and Sztorc (2013) the functional form of the damage function for coral reefs is fitted to the estimates from IPCC and Frieler et al. (2013) through a regression as described in section 3.1.

As a result the percentage loss of coral cover per temperature increase is given which can be used to calculate the absolute loss of coral cover in ha and the corresponding value loss using the results given in 4.2 and assuming constant values over time.
4.2 Fisheries

Fisheries is primary industry which for some states - especially for smaller states in the Indopacific - forms a significant basis for the whole economy. While the direct economic contribution from fisheries usually only considers the market value of the landed fish leaving the boat, this only reflects a small percentage of the real use of fish for self subsistence. In most cases fish is sold and processed further through various value chains and contributes to other economic sectors. Therefore, the fishing sector supports the economy in various ways through "trickle-up" effects. Furthermore, sectors such as boat building are tightly linked to the fishing sector. The overall impact of fisheries is determined through input-output analysis using data available from the Global Trade Analysis Project (Dyck and Sumaila 2010). In order to assess the full impact from changes in fish yield the total contribution of the fishing sector to global GDP is estimated through the multipliers provided in Dyck and Sumaila (2010).

The global landed value of fish is estimated to be 406 billion USD while the total economic impact of the sector is estimated at 1.3 trillion USD or 1.12 % of world GDP (FAO 2022; Dyck and Sumaila 2010). For the analysis of damages it is estimated that loss in landing value is proportional to loss in GDP from the fishing sector and that it therefore can be used as a proxy for GDP loss. Secondary sectors included in the overall GDP contribution of the fishing industries are for instance shipbuilding and the transport sector.

The here presented analysis only reflects estimations on the direct economic loss due to reduced revenue in the fishing sector and affiliated industries. However, it should be noted that this is most likely an underestimation of the total damages since socioeconomic impacts are not included. The dramatic reduction in catch potential around the tropics for instance can result in insufficient food provisioning for these regions, increased poverty and eventually migration movements.
4.3 Total Economic Losses

The overall results from section 3 and section 4 are shown in figure 4.1. The damages for each individual component (coral loss: blue; fisheries: orange) is shown as well as the overall loss for marine systems as assessed in this report (blue).

![Figure 4.1: Predicted damages related to ocean ecosystems.](image)

It can be seen that particularly damages to coral reefs are dominating in the temperature range up to 2 °C. As described it is assumed that virtually all coral reefs will be lost for a temperature increase beyond 2 °C which means that no further damage is added to this sector for further global warming.

For warming beyond 2 °C loss in fisheries revenue increases with a quadratic function, however, the impact is comparatively small. It is likely that other sectors and coastal as well as offshore ecosystems will be affected by global warming beyond 2 °C and thus will further add to the damages. Due to the lack of data and certainty of the development for temperature increases beyond 2 °C these damages are not included in this analysis. The here presented result should therefore be rather regarded as a conservative underestimate of the damages especially for larger temperature increases.
5 Model Results

In the following section the findings from the impact assessment and economic valuation of damages are compiled and resulting damage functions are derived. The damage functions are then implemented into the DICE model and the model outcomes are presented.

Deriving the damage function can be considered as a two step process. In a first step the different damage components are aggregated to a sum of damages including damages due to coral loss, loss in fisheries and damages related to other non-ocean sectors. In a second step a function is fitted to the data which is then implemented into the DICE model in order to compute the overall model results. The detailed process is further described below-

5.1 Damage Function

The damage function is aggregated consisting out of three components: (i) damages related to coral reef loss, (ii) damages relating to fisheries and (iii) damages related to market sectors considered in the damage functions presented in section 2.3. For the analysis of the results, both the damage function used in the DICE2016R2 model as well as the updated damage function from P. H. Howard and Sterner (2017) used by Hänsel et al. (2020) are considered. The total damage from ocean as well as non-ocean related damages is derived by superpositioning these three components.
Figure 5.1: Aggregated damage contributions compared to the DICE2016R2 damage function and the damage function in Hänsel et al. (2020).

Figure 5.1 shows the damages of each component as assessed in section 3 and section 4. The single components for coral loss and fisheries are shown (yellow and purple graph) as well as the aggregated damages including the damage functions presented in the DICE model as well as the update from Hänsel et al. (2020) (blue and blue dotted graph). The original functions from the DICE model and Hänsel et al. (2020) are shown as reference (red and green dotted graph).

It can be seen that damages related to the ocean, significantly change damage estimations for smaller increases in global atmospheric temperature until 2°C. These changes are mostly driven by the loss in coral reef. Up until 2.5°C ocean related damages are the dominant factor within the damage functions contributing more than 50% to the overall damages.

In order to be able to implement the assessed damages into the the DICE model, the compiled data needs to be described by a mathematical function.

In order to be able to implement the assessed damages into the the DICE model, the compiled data needs to be described by a mathematical function. Based on the results from the aggregation of damages, two different damage functions are developed which will be further implemented into the DICE model.

Both damage functions take the findings of this report into consideration and are
based on the same ocean related damage contributions. However, when it comes to
damages from other sectors, these damages are combined with the original damage
function developed by W. D. Nordhaus (2017) as well as the suggested update
by Hänsel et al. (2020). Both damage functions continue to follow a quadratic
relationship over the temperature increase (see figure 5.2).

The damage function based on the DICE version finds damages in the range
of 4.1% of total global GDP compared to 0.9% in the original version for a
temperature increase of 2°C and damages in the range of 7.1% compared to 2.1%
for a temperature increase of 3°C. Compared to the findings of P. H. Howard
and Sterner (2017) this damage function estimates higher damages up until a
temperature increase of 3.3°C. For higher temperatures P. H. Howard and Sterner
(2017) predict a stronger increase in damages.

5.2 Model Results

Using the DICE Ocean damage function results in a significant drop in maximum
temperature increase by 1.3°C form 4.2°C to 2.9°C compared to the original damage
function from the DICE 2016R2 model as shown in figure 5.3. This is much closer to
the commitments included in the Paris agreement considering that no other updates
are included in this version of the model.
When using updated version of the damage function used by Hänsel et al. (2020) the maximum temperature still decreases but the difference is much less significant. The update results in a drop of around 0.3°C.

The difference in sensitivity is explained by the structure of the damage function with the quadratic relationship of damages and temperature which also results in a larger spread of damage estimates for higher temperatures. Generally speaking, the uncertainty of damages for temperature increases above 3°C is still very high. However, runs with different damage functions have shown that the model is rather insensitive to the structure of the damage function for low temperature increases in the range up until 1.5°C. This can be partly explained by the high costs for abatement of CO₂ in the first years which correlate to the time period with a lower temperature increase. Furthermore, the model includes several technological as well as political restrictions such as from which year negative emissions are possible or the global emission control rate. These restrictions limit the possibility of quick and drastic abatement policies in the near term future which would prevent higher temperature increases and larger damages.

The development of the Social Cost of Carbon (SCC) follows a consistent pattern over the different damage scenarios as seen in figure 5.4. The highest SCC is calculated for damage function for the adjusted Hänsel et al. (2020) model while the lowest SCC is calculated for the original DICE damage function. However, as
previously mentioned the SCC is very sensitive to the inputs in the damage function and outcomes vary significantly between scenarios. For the year 2050 the model estimates SCC between 323 USD with the original DICE damage function and 1512 USD with the adjusted damage function used by Hänsel et al. (2020).

Figure 5.4: Social Cost of Carbon under different damage scenarios.
6 Discussion & Conclusions

The results give some clear indication that the assumptions made by W. D. Nordhaus (2017) regarding the damage function do not sufficiently reflect expected damages to marine based ecosystems and economic sectors. The biophysical evidence which is available today, suggests severe damages to marine ecosystems even for temperature increases which are in line with the commitments made in the Paris agreement.

So far these damages have been omitted mostly due to the lack of missing data. However, the literature review presented in this thesis shows that the literature availability for ocean related damages is twofold. On the one hand the literature on biophysical evidence and projections is constantly growing with increasing agreement and level of detail. On the other hand implementing this evidence into an economic framework still proves to be a challenging task with no methodological agreement between economic scholars. Even though there has been awareness for the issue since the late 90’s, modelling the relationship between ecosystems and the economy is still mostly on a conceptual level. This can be regarded as one of the biggest research gaps and barriers for gaining a holistic understanding of how our economy and society will be affected by climate change. The structure of the climate problem, with global externalities that cause damage on a very long time horizon, however, makes it necessary for us to gain the best and most complete understanding possible. Our actions today will determine the world of tomorrow and we need to understand the consequences of these in order to have the chance to change our society in a way which will not limit the opportunities of future generations.

Within this thesis, the findings have been implemented into the DICE model for global projections for the economy and climate change. However, the results from the biophysical evidence also show that the impact is very heterogeneous over different regions across the globe. Especially the tropics and subtropics are predicted to be affected much more than temperate zones or even the polar regions. This is particularly true for marine species and ecosystems which show stronger responses to temperature increases compared to many terrestrial ecosystems. Severely impacted marine ecosystems in the tropics often coincide with societies which rely on marine ecosystems the most, which can result in catastrophic outcomes for some regions. A number of secondary effects such as economic collapse, migration and social conflicts
can be the result which are not considered in detail within this report. For further research the implementation of marine based damages into IAMs such as the RICE model could help in identifying these secondary effects and gaining a more clear picture on the consequences of climate change on our society. The RICE model works structurally similar to the DICE model, but calculates development and impacts for specific regions instead of using globally aggregated data.

The use of regional models could additionally help in implementing further effects and ecosystems such as ocean acidification, mangrove and seagrass ecosystems as well as the effect of changed ocean currents. These areas do not show a clear indication of impacts due to climate change on a global scale since the effects are dependent on more factors than just atmospheric temperature. Local circumstances such as topography, urban development as well as the respective climate zone need to be included in the assessment in order to appropriately determine the consequences. Furthermore, in these areas there is indication that impacts can be negative for some regions while there might be beneficial effects in others. Differentiating the effects per region could help in outlining the overall consequences appropriately.

Finally, predictions for climate change as well as economic development is subject to a certain degree of uncertainty. Particularly the inclusion of ecosystems into the evaluation raises uncertainties which increases the question whether such a perspective should be pursued after all. However, not implementing ecosystems into the evaluation and therefore ignoring their significance and relationship to society essentially assigns them a value of 0. While the value for ecosystems is uncertain, it is unarguably not 0. A value for ecosystem services above 0 is subject to uncertainty, a value of 0 is certainly wrong. Similar arguments have already been made for the general introduction of carbon prices and they also hold up for the inclusion of ecosystem services into the calculation.
References


ESVD (2022). Ecosystem Services Valuation Database. URL: https://www.esvd.net/ (visited on 02/15/2023).


Pindyck, Robert S (2013). “Climate change policy: what do the models tell us?” In: *Journal of Economic Literature* 51.3, pp. 860–872.


Rivera, Hanny, Chan, Andrea, and Luu, Victoria (Aug. 2020). “Coral reefs are critical for our food supply, tourism, and ocean health. We can protect them from climate change”. In: *MIT Science Policy Review* 1, pp. 18–33. doi: [10.38105/spr.7vn798jnsk](http://10.38105/spr.7vn798jnsk).


7 Appendices

7.1 Appendix A: Results from change in economic model

The following figures show the results of the changes in the economic model are shown in as described in 2.4.1. It can be observed that the model behaves similarly no matter whether ecosystem services are included in the economic output model or not. The optimal temperature increase estimated by the model remains around 4 (see figure 7.2 and the SCC peaks around 2.200 USD/t CO2 (see figure 7.1) in both models. Abatement costs and economic output behave structurally similar with different magnitudes which is explained by the inclusion of ecosystem services and a higher total output.

Figure 7.1: Social Cost of Carbon between original DICE Model (R2) and model including ecosystem services (R3)
Figure 7.2: Temperature change and change in CO2 concentration between original DICE Model (R2) and model including ecosystem services (R3)
7.2 Appendix B: Model Results

The figures in this appendix describe the model results including the changed economic description as explained in section 2.4.1 as well as several different damage functions. Namely these are the damage function from the original DICE model (referred to as DICE2016R3), the damage function described in Hänsel et al. 2020, the damage function from the original DICE model updated with the findings of this report (referred to as DICE2016R3 Ocean) as well as the damage function described in Hänsel et al. 2020 updated with the findings of this report (referred to as Ocean + Hänsel).

Figure 7.3: Temperature increase under different damage scenarios

Figure 7.4: Social Cost of Carbon under different damage scenarios
Figure 7.5: Damages under different damage scenarios
7.3 Appendix C: GAMS Code

In the following the GAMS code used to compute the results which are described in this thesis is presented. Generally, the structure and inputs are the same as in the DICE2016R2 code. Changed input parameters are the damage function control parameters (a1-a5). Furthermore, the economic module has been adjusted as described in section 2.4.1 through the introduction of parameters s0, r0 and teta which are further used in the description of the economic model (YGROSS(t)).
$context$
This is the beta version of DICE-2016R. The major changes are outlined in Nordhaus, "Revisiting the social cost of carbon: Estimates from the DICE-2016R model," September 30, 2016," available from the author.

$version$
DICE-2016R-091916ap.gms

$title$
DICE-2016R September 2016 (DICE-2016R-092226a.gms)

parameters
$net$
t Time periods (5 years per period) /1*100/

** availability of fossil fuels**
fossil Maximum cumulative extraction fossil fuels (GtC) /6000/

** time step**
tatep Years per Period /5/

** if optimal control**
topt Indicator where optimized is 1 and base is 0 /1/

** preferences**
elasmu Elasticity of marginal utility of consumption /1.45/
prcstp Initial rate of social time preference per year /0.15/

** population and technology**
gamm Capital elasticity in production function /3.30/
alpha population elasticity in production function /0.60/
teta exponent for biosphere part in production function /0.20/
ppcp0 Initial world population 2015 (millions) /7403/
popadj Growth rate to calibrate to 2050 pop projection /0.134/
popasym Asymptotic population (Millions) /1150/
dk Depreciation rate on capital (per year) /1.00/
q0 Initial world gross output 2015 (trill 2010 USD) /105.5/
k0 Initial capital value 2015 (trill 2010 USD) /215.97/
r0 Biosphere Stock (trillions) /17.13/
s0 Initial level of total factor productivity /5.11/
s1 Value of ecosystem services (trillion) /76.83/
g0 Initial growth rate for TFP per 5 years /0.076/
nde Decline rate of TFP per 5 years /0.005/

** emissions parameters**
gsigmal Initial growth of sigma (per year) /-0.0152/
dsig Decline rate of decarbonization (per period) /-0.001/
e1and0 Carbon emissions from land 2015 (GtCO2 per year) /2.6/
deland Decline rate of land emissions (per period) /-0.115/
e0 Industrial emissions 2015 (GtCO2 per year) /35.85/
e1l0 Initial emissions control rate for base case 2015 /0.03/

** carbon cycle**
* initial conditions*
m0 Initial Concentration in atmosphere 2015 (GtC) /851/
m50 Initial Concentration in upper strata 2015 (GtC) /460/
m10 Initial Concentration in lower strata 2015 (GtC) /1740/
meq Equilibrium concentration atmosphere (GtC) /588/
meq Equilibrium concentration in upper strata (GtC) /360/
meq Equilibrium concentration in lower strata (GtC) /1270/

* flow parameters*
b12 Carbon cycle transition matrix /0.12/
b33 Carbon cycle transition matrix /0.007/

* these are for declaration and are defined later*
b11 Carbon cycle transition matrix
b21 Carbon cycle transition matrix
b22 Carbon cycle transition matrix
b32 Carbon cycle transition matrix
b33 Carbon cycle transition matrix

** climate model parameters**
txco2 Equilibrium temp impact (°C per doubling CO2) /3.1/
fxco2 2015 forcings of non-CO2 GBE (Wm-2) /0.5/
fxco2 2100 forcings of non-CO2 GBE (Wm-2) /1.0/
tocetm0 Initial lower stratum temp change (°C from 1900) /0.068/
tamatm0 Initial atmospheric temp change (°C from 1900) /0.85/
c3 Transfer coefficient upper to lower stratum /0.088/
c4 Transfer coefficient for lower level /0.025/
fe2x2x Forcings of equilibrium CO2 doubling (Wm-2) /3.6813/
** Climate damage parameters

a10  Initial damage intercept /0 /
a20  Initial damage quadratic term /0 /
a1  Damage intercept /0 /
a2  Damage quadratic term /0.0236 /
a3  Damage exponent /2.00 /

** Abatement cost

expost2  Exponent of control cost function /2.6 /
pback  Cost of backstop 2010$ per TCO2 2015 /560 /
pbcrk  Initial cost decline backstop cost per period /0.025 /
lumb  Upper limit on control rate after 2150 /1.2 /
tmvpol  Period before which no emissions controls base /45 /
cprize0  Initial base carbon price (2010$ per TCO2) /2 /
gcprice  Growth rate of base carbon price per year /0.02 /

** Scaling and inessential parameters

* Note that these are unnecessary for the calculations

* They ensure that MS of first period's consumption = 1 and PV cost = PV utility

scale1  Multiplicative scaling coefficient /0.03902455265681763 /
scale2  Additive scaling coefficient /-10993.704 /

* Program control variables

sets tfirst(t), tlast(t), teary(t), tlate(t);

PARAMETERS

l1(t)  Level of population and labor
a1(t)  Level of total factor productivity
sigma(t)  CO2-equivalent-emissions output ratio
rr(t)  Average utility social discount rate
gs(t)  Growth rate of productivity from
fooroth(t)  Exogenous forcing for other greenhouse gases
gl(t)  Growth rate of labor
gcost(t)  Growth of cost factor
gsig(t)  Change in sigma (cumulative improvement of energy efficiency)
etre(t)  Emissions from deforestation
cumtree(t)  Cumulative from land
cost(t)  Adjusted cost for backstop
lam  Climate model parameter
gfacpop(t)  Growth factor population
gbacktime(t)  Backstop price
optlsee  Optimal long-run savings rate used for transversality
sc(t)  Social cost of carbon
cpricest(t)  Carbon price in base case
pholst(t)  Carbon Price under no damages (Notelling rest condition)
gpm(t)  Atmospheric concentrations parts per million
atfrac(t)  Atmospheric share since 1850
atfrac2010(t)  Atmospheric share since 2010 ;

* Program control definitions

tfirst(t) = yes[$(t.val eq 1)]
tlast(t) = yes[$(t.val eq card(t));

* Parameters for long-run consistency of carbon cycle

b1 = 1 - b22;
b21 = b12*MATEQ/MUSEQ;
b22 = 1 - b21 - b23;
b32 = b23*MEQ/MLEQ;
b33 = 1 - b23 ;

* Further definitions of parameters

a20 = a2;
sigp = e0/(q0*(1-miu0));
lem = fco22/2*2co2;
lro(t) = popo2;
loop(t, [t==1]-[t==25]);
loop(t, [t==1]-[t==50]);
gs(t)=gsig*exp[-delta^*(t.val-1)];
sig2(t)=sig2(t-1); loop(t, [t==1]-[t==25]);
loop(t, [t==1]-[t==50]);
sigma2(t)=sig2(t); loop(t, [t==1]-[t==50]);
psig(t)exp[gsig*(t.val-1)];
pholst(t) = pholst2*yes[$(t.val eq 1)];

cost(t) = gbacktime(t)*sigma(t)/expost2/1000;
etree(t) = (lambd*1-land)[$(t.val eq 1)];
cumtree(t) = cumtree(t)*t/3.6666666);
rr(t) = 1/[1+prst(t)];
forst(t) = fex0 *(1/17)*fes(t-10)*fes(t-10)*fes(t-10)*((t.val ge 10);
optlsee = (dk + .004)/dk + .004*elasms + prst*gam;

*Base Case Carbon Price
cpricest(t) = cprice0*(1+gcprice)*5^t.val-1);
VARIABLES
MIU(t) Emission control rate GHSs
FUNC(t) Increase in radiative forcing (watts per m2 from 1900)
TATM(t) Increase temperature of atmosphere (degrees C from 1900)
TOCEAN(t) Increase temperature of lower oceans (degrees C from 1900)
MO(t) Carbon concentration increase in atmosphere (GTC from 1750)
ML(t) Carbon concentration increase in lower oceans (GTC from 1750)
E(t) Total CO2 emissions (GTC2 per year)
EIND(t) Industrial emissions (GTC2 per year)
C(t) Consumption (trillions 2005 US dollars per year)
K(t) Capital stock (trillions 2005 US dollars)
P(t) Per capita consumption (thousands 2005 USD per year)
S(t) Gross savings rate as fraction of gross world product
W(t) Gross world product net of abatement and damages (trillions 2005 USD per year)
YGROSS(t) Gross world product GROSS of abatement and damages (trillions 2005 USD per year)
YNET(t) Output net of damages equation (trillions 2005 USD per year)
NW(t) Damage (trillions 2005 USD per year)
SABATEE(t) Damage as fraction of gross output
ABATECOST(t) Cost of emissions reductions (trillions 2005 USD per year)
MCABATE(t) Marginal cost of abatement (2005S per ton CO2)
CCA(t) Cumulative industrial carbon emissions (GTC)
CADCOT(t) Total carbon emissions (GTC)
PERIODIC(t) One period utility function
CPEX(t) Carbon price (2005S per ton of CO2)
UTILITY Welfare function

NONNEGATIVE VARIABLES MIU, TATM, NW, MO, ML, Y, YGROSS, C, K, I;

EQUATIONS

*Emissions and Damages
EEQ(t) Emissions equation
EIND(t) Industrial emissions
CAG(t) Cumulative industrial carbon emissions
CAGT(t) Cumulative total carbon emissions
NRE(t) Radiative forcing equation
SABATEE(t) Equation for damage fraction
ABATECOST(t) Cost of emissions reductions equation
MCABATE(t) Equation for NW abatement
CARPRICE(t) Carbon price equation from abatement

*Climate and carbon cycle
MAT(t) Atmospheric concentration equation
MNL(t) Shallow ocean concentration
MAT(t) Lower ocean concentration
TOCEAN(t) Temperature-climate equation for atmosphere
TOCEON(t) Temperature-climate equation for lower oceans

*Economic variables
YHGDSEQ(t) Output gross equation
YHEQB(t) Output net of damages equation
YF(t) Output net equation
CC(t) Consumption equation
PCP(t) Per capita consumption definition
SEQ(t) Savings rate equation
KB(t) Capital balance equation
RIE(t) Interest rate equation

* Utility
CDWINDEQ(t) Period utility
PERIODIC(t) Instantaneous utility function equation
UTILITY Objective function
** Equations of the model

*Emissions and damages

\[ \text{seq(t), e(t)} \]
\[ \text{EIND(t)} = E \text{EIND(t) + etree(t)}; \]
\[ \text{e(t)} = \text{EIND(t) + \text{YPROSS(t) * (1-\text{MIFU(t)})}}; \]
\[ \text{ccacco(t)} = \text{CCA(t) + EIND(t)/5.3.666}; \]
\[ \text{costa(t)} = \text{CCA(t) + custime(t)}; \]
\[ \text{force(t)} = \text{fco2x * ((log(MAT(t)/585.000))/log(2)) + fco2x(t)}; \]
\[ \text{damfrac(t)} = \text{DAMFRAC(t) = ((1+\text{TnEM(t)}) * (1+\text{TnEM(t)}) * \text{a2}}; \]
\[ \text{damseq(t)} = \text{DAMSEQ(t) = \text{YPROSS(t) + DAMFRAC(t)}; \]
\[ \text{abateeq(t)} = \text{ABATEOCT(t) = \text{YPROSS(t) * costl(t) + \text{MIFU(t)**expco2*2}}; \]
\[ \text{mcbateeq(t)} = \text{MCBATE(t) = \text{pbacktime(t) * (MIFU(t)**expco2-l)}}; \]
\[ \text{cpriceeq(t)} = \text{CFRICE(t) = \text{pbacktime(t) * (MIFU(t)**expco2-l)}}; \]

*Climate and carbon cycle

\[ \text{natm(t+1)} = \text{MAT(t+1)} = \text{MVT(t)**big + \text{MTH(t)**big + E(t)**(5.3.666)}}; \]
\[ \text{nmm(t+1)} = \text{Ht(g)**big + \text{MTH(t)**big + MTH(t)**big}}; \]
\[ \text{num(t+1)} = \text{MVT(t)**big + \text{MTH(t)**big + MTH(t)**big}}; \]
\[ \text{natmseq(t+1)} = \text{TETH(t+1)} = \text{TATH(t) + cl * ((F00C(t)+1-t2co2*t2co2)*TATH(t)-(C3)*TATH(t-OCEAN(t)))}}; \]
\[ \text{toceaneq(t+1)} = \text{TOCEAN(t) = \text{C3}*(TATH(t)-TOCEAN(t))}; \]

*Economic variables

\[ \text{yproseq(t)} = \text{YPROSS(t) = \text{a1(t)**(L(t)/1000)**(ALPHA)**(K(t)**GAMA)**(X0)**(1-ALPHA-GAMA)**X0**TETA; \]
\[ \text{ymteq(t)} = \text{YMT(t) = \text{YPROSS(t) - \text{DAMFRAC(t)}}; \]
\[ \text{jj(t)} = \text{Y(j(t) - \text{ABATEOCT(t)}}; \]
\[ \text{cc(t)} = \text{C(t) = \text{Y(t) - I(t)}}; \]
\[ \text{cpc(t)} = \text{CFC(t) = \text{1000 * C(t) / L(t)}}; \]
\[ \text{seq(t)} = \text{I(t) = \text{G(t) + Y(t)}}; \]
\[ \text{kk(t+1)} = \text{K(t+1) = \text{L*(1-D)**tstep} + \text{K(t) + tstep} + \text{I(t)-I0)}}; \]
\[ \text{riel(t+1)} = \text{RI(t) = \text{I+prest plus \text{CFC(t+1)/CFC(t)**(elasmu/tstep)} - I}}; \]

*Utility

\[ \text{cematot} = \text{CEMUTOT(t) = \text{PERIOD(t) * L(t) * T(t) + T(t)}}; \]
\[ \text{periodo} = \text{PERIOD(t) = \text{X(C(t)**1000/L(t))**(1-ELASMU)-1)/(1-ELASMU)-1}}; \]
\[ \text{util} = \text{UTILITY = tstep * scalel * sum(t, CEMUTOT(t)) + scale2}; \]

*Resource limit

\[ \text{CCA.up(t) = fosslim}; \]

* Control rate limits

\[ \text{MIFU.up(t) = lismu; \]
\[ \text{MIFU.up(t)+t.val<30} = 1; \]

** Upper and lower bounds for stability

\[ \text{L.LO(t) = 1; \]
\[ \text{MAT.LO(t) = 10; \]
\[ \text{ML.LO(t) = 100; \]
\[ \text{ML.LO(t) = 1000; \]
\[ \text{C.LO(t) = 2; \]
\[ \text{TOCEAN.LO(t) = 20; \]
\[ \text{TOCEAN.LO(t) = -1; \]
\[ \text{TATH.UP(t) = 20; \]
\[ \text{CPC.UP(t) = 10; \]
\[ \text{TATH.UP(t) = 12; \]

* Control variables

\[ \text{set lag10(t); \]
\[ \text{lag10(t) = yes[t.val> card(t)-10); \]
\[ \text{s.FX(lag10(t) = optlemav}; \]

* Initial conditions

\[ \text{CCA.FX(first) = 400; \]
\[ \text{R.FX(first) = 40; \]
\[ \text{MAT.FX(first) = mat0; \]
\[ \text{ML.FX(first) = nu0; \]
\[ \text{ML.FX.first) = ml0; \]
\[ \text{TATH.FX(first) = tatem0; \]
\[ \text{TOCEAN.FX(first) = toceano}; \]
** Solution options
option iterlim = 99999;
option realnum = 99999;
option solprint = on;
option lpsrow = 0;
option lpscol = 0;
model CO2 /all/;

* For base run, this subroutine calculates Netting rents
* Carbon price is maximum of Netting rent or baseline price
* The price equation is different from 2013R. Not sure what went wrong.
if (ifo1 eq 0,
  a1 = 0;
  solve CO2 maximizing U1 using nlp;
    npvopt(t) = cprice(t);1(t);
  a2 = a2v;
  cprice-upt(t) = (t.val<nopolo>1) = max(npvopt(t),cpricebase(t));
);

mu1.fx('1')$4(ifo1=1) = mu1u;
solve CO2 maximizing utility using nlp;
solve CO2 maximizing utility using nlp;
solve CO2 maximizing utility using nlp;

** POST-SOLVE
* Calculate social cost of carbon and other variables
acc(t) = 180000*exp.m(t)(/.00001+cc.m(t));
attrac(t) = (mat.l(t)-588)/1/ccoatol.1(t)+.00001. );
attrac2010(t) = (mat.l(t)-mat01/0.00001+ccoatol.1(t)-ccoatol.1'1' )
pvcc(t) = mat.l(t)/2.33;

* Produce a file "Dice2015R-091916ap.csv" in the base directory
* For all relevant model outputs, see PostOutputAll.txt in the Include folder.
* The statement at the end of the .lst file "Output...." will tell you where to find the file.

dice2016R-091916ap.csv;
results.nd = 10 ; results.mw = 0 ; results.pw=20000; results.pc=5;
results;
put "Results of DICE-2016R model run using model Dice2015R-091916ap.csv"
put "This is optimal if ifo1 = 1 and baseline if ifo1 = 0"
put "ifo1 = ifo1p"
put // "Period"
loop (t, put t.val):
  put / "Year"
  loop (t, put (2010+STEP*T.val) ));
  put / "Annual Emissions N2O per year"
  loop (t, put EEMO.1(T)));
  put / "Atmospheric Concentration C (ppm)"
  loop (t, put (mat.l(t)/2.13));
  put / "Atmospheric Temperature *'
  loop (t, put TSEM.L1(T));
  put / "Output Net Net";
  loop (t, put Y.L1(T));
  put / "Climate change fraction output";
  loop (t, put DAEFFAC.1(T));
  put / "Consumption per Capita *'
  loop (t, put CFCO.L1(T));
  put / "Carbon Price (per t CO2)";
  loop (t, put cprice.1(T));
  put / "Emissions Control Rate";
  loop (t, put MUL.1(T));
  put / "Social cost of carbon";
  loop (t, put scco(T));
  put / "Interest Rate *'
  loop (t, put I.T1(L));
  put / "Population";
  loop (t, put L(T));
  put / "TFP"
  loop (t, put AL(T));
  put / "Output gross, gross";
  loop (t, put YUORGE.1(T));
  put / "Change tpf"
  loop (t, put ga(T));
  put / "Capital";
Loop (T, put k1_l(t));
put / "T" ;
Loop (T, put s1_l(t));
put / "s" ;
Loop (T, put i1_l(t));
put / "i" ;
Loop (T, put ysat_l(t));
put / "ysat" ;
Loop (T, put damages_l(t));
put / "damages" ;
Loop (T, put damfrac_l(t));
put / "damfrac" ;
Loop (T, put abatecost_l(t));
put / "abatecost" ;
Loop (T, put sigma_l(t));
put / "sigma" ;
Loop (T, put forcings_l(t));
put / "Forcings" ;
Loop (T, put forc1_l(t));
put / "Forcings1" ;
Loop (T, put forc0_l(t));
put / "Forcings0" ;
Loop (T, put periodL1_l(t));
put / "periodL1" ;
Loop (T, put periodL2_l(t));
put / "periodL2" ;
Loop (T, put C1_l(t));
put / "C1" ;
put / "Utility" ;
put / "Land emissions" ;
Loop (T, put etree_l(t));
put / "Cumulative land emissions" ;
Loop (T, put cca_l(t));
put / "Cumulative total emissions" ;
Loop (T, put co2tot_l(t));
put / "Atmospheric concentrations CO2" ;
Loop (T, put mat_l(t));
put / "Atmospheric concentrations ppm" ;
Loop (T, put ppm_l(t));
put / "Total Emissions GtCO2 per year" ;
Loop (T, put E1_l(t));
put / "Atmospheric concentations upper" ;
Loop (T, put nu_l(t));
put / "Atmospheric concentrations lower" ;
Loop (T, put nl_l(t));
put / "Atmospheric fraction since 1850" ;
Loop (T, put atfrac_l(t));
put / "Atmospheric fraction since 2010" ;
Loop (T, put atfrac2010_l(t));
putclose;