Chapter ???

Economic damage of climate change: How far is it from the physical damage?

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Costs of climate change in integrated assessment models (IAMs) are in most cases based on a fixed relationship between a change in mean temperature and a change in the value added. The consequences of economic behavior, measures taken to adapt specifically to expected climatic changes and resulting market effects are thereby omitted. This chapter shows how attention to these factors affects estimates of the costs of climate change. With a given physical effect on grain yield as the point of departure, we show how the economic impacts depend on assumptions related to adaptation within the agricultural sector throughout the world. In an average 2100 climate, the economic impacts of a 2.3-percent reduction in the productivity of grain under present economic conditions ranges between 0 to 2.3 percent of the sum of GDP in all world regions, depending on opportunities for adaptation, but between -25 and 70 percent of the GDP on regional levels. Changes in relative prices across sectoral products modify considerably the economic damage estimated at constant prices. The regional GDP calculated at purchasing power parities (PPP) used in many studies tends to be too optimistic to indicate the economic damages particularly in developing countries. Hence, GDP deflated at local consumer price index is recommended to indicate the regional rather than global economic damages in these countries. The regions depending heavily on agriculture are suggested to reduce their dependence on agriculture during the economic development to be better prepared for the potential economic consequences of climate change.

1. Introduction

In the integrated assessment models (IAMs) like DICE (Nordhaus, 1993) and FUND (Tol, 1997), the optimal paths of emissions and social cost of carbon are sensitive to the specification of climate damage functions (Wouter Botzen and van den Bergh, 2012, Dayaratna et al., 2017), which show the impact on an economic aggregate (e.g. value added) of increasing changes in temperature. The functions are usually calibrated under a given change in temperature or concentrations of CO_2. The impacts follow a choice of functional form under increasing climate change, e.g., the quadratic form proposed by Nordhaus (2008) or a highly nonlinear form proposed by Weitzman (2012), where the latter is more sensitive to high temperature increases.

The damage functions are, in principle, based on quantifications of the physical impacts of climate change. They can be estimated by statistical methods (Mendelsohn et al., 2000, Nordhaus, 2006, Lemoine and Kapnick, 2016) or meta-analysis (Fankhauser, 1995, Tol, 2002). Regardless of method, the fixed linkage between indicators for a change in climate and an economic aggregate is subject to a range of assumptions, which implies a considerable uncertainty related to the estimates of economic impacts of climate change (van den Bergh and Botzen, 2015). The impact on an economic aggregate due to a change in grain yield caused by climate change, for example, can be estimated as the physical effect on grain yield multiplied by a constant price. This estimation implies that the impacts on grain yields do not affect the production or consumption of grain products in any way. The following possibilities are thereby excluded:

1. If the physical damage implies a change in the productivity of land, the economic damage will depend on how the producers adapt, with further consequences for the use of other input factors.
2. How the producers adapt depends on their possibilities to compensate a reduction in the productivity of land with more work or with alternative technologies.

3. Adaptation implies that producers of grain will use more (or less) labor and other production factors, with consequences for other production activities in the economic system.
4. A damage in the production of grain will enforce a reduction in the consumption of grain products, and the economic impacts will depend on how consumers replace their use of grain products.

This chapter addresses what these factors imply for assessments of the economic impacts of climate change. For illustration, we take given estimates of the impacts on grain yields in physical terms in different world regions as a point of departure and estimate the economic impacts under different assumptions. Particular attention is paid to the impacts on relative prices, which help to explain the drivers behind the differences in the impact estimates.

Notably this study finds that, among others, the regional GDP calculated at purchasing power parities (PPP) used in many studies tends to be too optimistic to indicate the regional economic damages in developing countries although it is plausible for estimating the global damages. Hence, GDP deflated at local consumer price index, as a better indicator of regional welfare, is recommended to indicate the regional rather than global economic damages in developing countries.

The chapter is organized as follows. The next section presents the methods used in this study. Section 3 reports results and provides further discussion. Section 4 concludes the chapter.

2. Methods

First, we use a simple theoretical model to highlight the assumptions underlying different estimates of the economic impacts of a given physical effect of climate change in one sector, grain production, in a closed economy. Next, we present the numerical global model used to quantify the economic impacts of climate change on grain production under alternative assumptions on production and consumption functions in different world regions.

2.1. *The theory underlying cost estimates*

To show the implications of alternative quantifications of the economic consequences of climate change, we take the intuitive definition of the economic impact, reflected by point 1 above, as our point of departure. Then, we simplify the description of the economy by assuming a closed economy with a fixed capital stock without depreciation. In that case, the value added across all sectors (Y) or gross domestic product (GDP), equals consumption (C). The value of physical quantities produced in an economy that is divided into two sectors, grain production (Y_G) and production of other goods (Y_N), for example, is found by the quantities multiplied with their respective prices, P_G and P_N, which thereby applies as a measure of welfare:

$$C = P_G C_G + P_N C_N = P_G Y_G + P_N Y_N = Y. \tag{1}$$

Climate change will affect both the production of grain and the production of other goods. If there are no ways to reallocate the resources needed to produce the two goods and the market prices remain unaffected, the economic impacts of climate change, and thereby the change in consumption, can be estimated as

$$dC = P_G dY_G + P_N dY_N, \tag{2}$$

which corresponds to the intuitive estimate of economic impacts reflected by point 1 above.

If the impacts cause a reallocation of resources used to produce grain and other goods, for example because production of grain implies that some farmers have to close down and are employed in production of other goods, and preferences of consumers may adapt to the impacts, then the physical impacts will also lead to a change in prices. Hence, the economic impact of climate change must include the real price change effect besides the physical damage impacts (Asheim and Wei, 2009),

$$dC = \underbrace{Y_G dP_G + Y_N dP_N}_{\text{price change effect}} + \underbrace{P_G dY_G + P_N dY_N}_{\text{physical quantity effect}} . \tag{3}$$

In practice, the price change effect can be considerable and even greater than the physical quantity effect for grain products since the majority of grain products are food to satisfy the sustained demand of consumers, which is necessary even if prices become very high, i.e., the demand is price-inelastic. Hence, estimates of the economic impacts of climate change must take the impacts on prices into account, to include the socioeconomic consequences of adaptation to climate change among economic agents.

To illustrate the economic mechanisms underlying the socioeconomic impacts of climate change, we assume that production of grain and other goods are subject to the following production functions:

$$Y_G = f(K_G, \bar{L}, T);\ Y_N = g(K_N) = g(\bar{K} - K_G), \tag{4}$$

where K_G and K_N are capital inputs covering all productive resources in production of grain and other goods, respectively, excluding land used for grain production ($\bar{L}$), and T is an indicator for the climate, which is often represented by mean temperature. Here, the physical effects of climate change are limited to grain production, while the production of other goods is affected only indirectly by the reallocation of productive resources between the two sectors that follows from the impacts on the production of grain. To get as much as possible out of the productive resources assuming constant prices, the marginal productivity of these resources will be equalized in the two sectors, meaning that $P_G f_1 = P_N g_1$ in the optimal case. Then we have

$$P_G dY_G + P_N dY_N = P_G(f_1 dK_G + f_3 dT) - P_N g_1 dK_G = P_G f_3 dT. \tag{5}$$

which seems to justify that the economic damage at constant prices can be assessed by the cost of the physical damage of climate change, dT, as assumed in (2). However, the grain price (P_G) would not keep constant since grain output is damaged by climate change. In addition, the condition of equalized marginal productivity of all resources ($P_G f_1 = P_N g_1$) is unrealistic when an economy is disturbed by the impact of climate change on grain production. Climate change may imply a change in the variability of weather over the seasons, with new challenges to the planning of the timing of sawing and choice of equipment. The equipment cannot be reallocated to production of other goods overnight, however, meaning that the marginal productivity of capital in grain production will differ from that of capital assets in other sectors at least in the short run. Then, the second equation of Eq. (5) is no longer valid. To capture the economic damage in such sub-optimal cases, the calculations below assume there is no substitution between capital assets in production of grain and in other production activities, while there is full substitution between labor in the two sectors.

To adapt to changes in long-term trends in climate, producers will try to adjust their use of input factors in the production of grain. This implies that all the resources used in production will be reallocated between grain production and other sectors, until the marginal productivity of all resources is the same in both sectors in the optimal case. There are at least two ways to represent this adjustment in the modelling. One is based on Hicksian neutral technology and the other on attaching the impacts to the productivity of land, i.e.,

$$Y_G = A(T)h(K_G, \bar{L}) \quad or \;\; Y_G = Ah(K_G, \tau(T)\bar{L}). \tag{6}$$

The first alternative (Hicksian) reflects the case where producers of grain apply the same production method and technology from the existing one, regardless of climate. In that case, producers find it unnecessary to adapt to climate change by adjusting the composition of input factors. The only change is the scale of production. For example, if an extreme event like a flood occurs just before the harvest of grain, no adaptation measures would help to reduce the damage on the grain yields. Another example is if climate change implies a reduction in the production of grain, the number of farms may be reduced, but the remaining farms continue as before, without any adjustments in the way they produce grain, e.g. by investments in irrigation and other machinery. In such cases, the Hicksian production form is plausible.

The second alternative applies if climate change motivates measures to adapt to new constraints related to impacts on the productivity and availability of land, such as the use of labor, machinery, and irrigation systems. While the means of production other than land are unaffected by the climatic changes themselves, producers will adapt to a change in the productivity of land by changing the use of the other means of production. As the adaptation can be reflected by the technology options described by the production functions in the model, the impact of climate change can be attached to the productivity of land in this case. Then, the model allocates other means of production according to the availability of all the resources, which reflects adaptation in a broad, socioeconomic context. In the next section, we estimate the socioeconomic impacts of climate change on grain production in both cases assuming fully mobile labor and still immobile capital assets across sectors in a static numerical model. Notice that we do not simulate the fully optimal case since the reallocation of capital assets across sectors is not considered although it might happen to some extent in the longer run.

The changes in grain production will affect the production of other goods as well, due to less available grain products as intermediate inputs and the reallocation of labor and other intermediate inputs, although the reallocation of capital assets is not allowed in our numerical simulation below. This leads to a change in prices, which also depends on consumers' demand. This demand is derived from the utility function of consumers, which in this simplified illustrative model is a function of the two aggregated goods,

$$U = u(C_G, C_N). \tag{7}$$

Utility maximization yields

$$P_G = \frac{\partial u(C_G, C_N)}{\partial C_G}, \quad P_N = \frac{\partial u(C_G, C_N)}{\partial C_N}\ . \tag{8}$$

The impacts on prices thereby depend on the choice of functional form of the utility functions. To capture the influence of this choice, we will, in the numerical model below, consider three types of utility functions: constant elasticity of substitution (CES), Cobb-Douglas (elasticity of substitution = 1), and Leontief (elasticity of substitution = 0).

To sum up, the calculations address the economic impacts of a given physical impact of climate change on the productivity of land in production of grain by using two different grain production functions, and three alternative consumption functions.

2.2. *The numerical model*

We examine how the different assumptions affect the estimates of economic damage due to climate change by using a static multi-sector, multi-regional global computable general equilibrium (CGE) model GRACE (Aaheim and Rive, 2005, Aaheim et al., 2018, Carattini et al., 2019, Wei et al., 2019). The model has been applied to studies on climate impact, adaptation, mitigation, and related policy analysis (e.g., Aaheim et al., 2012, Glomsrød et al., 2013, Underdal and Wei, 2015, Glomsrød et al., 2016, Wei et al., 2017, Orlov et al., 2020). In this study, we adopt the version of GRACE in Wei et al. (2019), which is based on the 2011 global economic data from the Global Trade Analysis Project (GTAP) database v.9 (Aguiar et al., 2016). In the model, the world is divided into 140 regions and a regional economy consists of 14 production sectors including four agricultural sectors, two food sectors, one manufacturing sector, one transport sector, one services sector and five energy sectors.

The four agricultural sectors produce wheat, rice, maize, and other agricultural products, respectively. In this study, the default production functional form for these agricultural sectors is a nested CES function described in Fig. 1. The top-level combines land (RES) with an aggregate of all other input factors, which are divided into a Leontief composite of

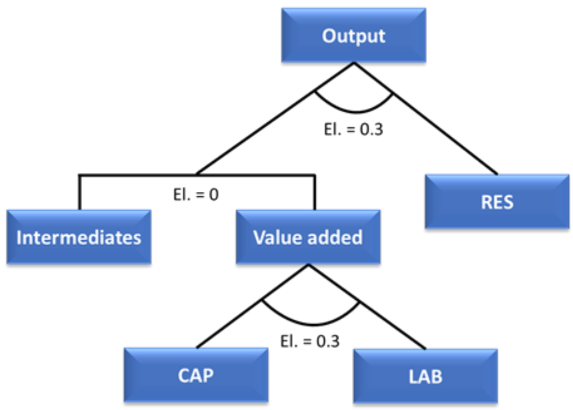

Fig. 1. Default production structure of agricultural sectors in GRACE. “El.” refers to the chosen elasticities of substitution for the components in each aggregate.

intermediate goods and value-added, where the value-added combines capital (CAP) and labor (LAB).

This study also addresses the implications of alternative demand structures for consumers. The default demand structure in GRACE is shown in Fig. 2. At the top level, substitution can be made between energy and the other goods (non-energy). At the bottom level, the energy combines five energy goods (i.e., coal, crude oil, gas, refined oil and electricity) and the non-energy combines all the other goods.

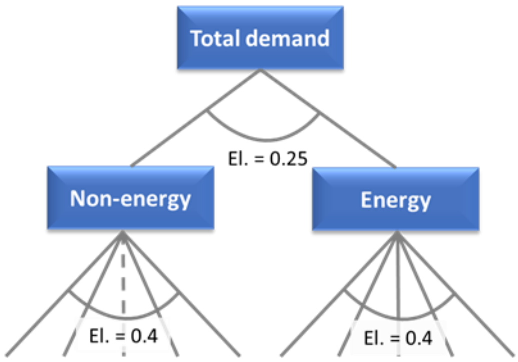

Fig. 2. Default final demand structure in GRACE. "El." refers to the chosen elasticities of substitution for the components in each aggregate.

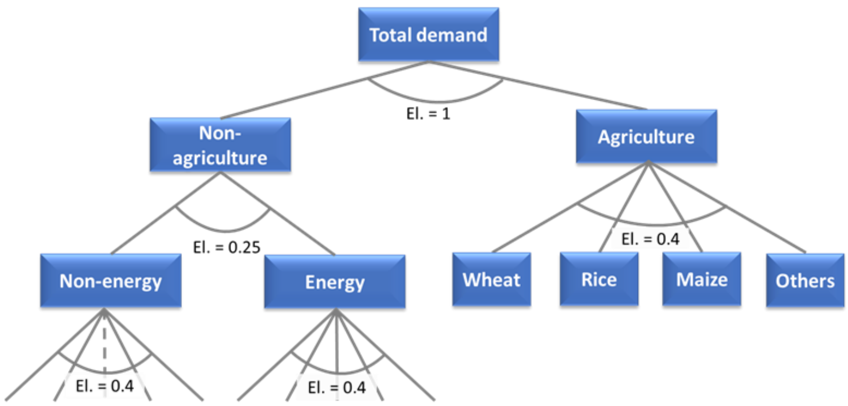

Fig. 3. Alternative final demand structure in GRACE. "El." refers to the chosen elasticities of substitution for the components in each aggregate.

To examine the effect of alternative demand structures of households, we introduce the other demand structure by moving the aggregated agricultural products to the top level combined with the other products (Fig. 3). If the substitution elasticity of this level is 1 corresponding to the Cobb-Douglas combination, consumers will spend the same share of their total income on agricultural products and the other goods. If the elasticity is 0 corresponding to the Leontief combination, then consumers prefer to consume the same combination of agricultural products and the other goods in physical terms, rather than monetary terms. The demand for the other consumer goods follows the same structure as shown in Fig. 2.

The other settings of the model are the same as in the version described in detail in Aaheim et al. (2018), which shows the structure of the model, how the parameters are calibrated, and specifications of the preferences and technologies in GRACE.

2.3. *Alternative cases to estimate economic damage*

We calibrate GRACE to the 2011 global economic data described in the GTAP database v.9 (Aguiar et al., 2016), which gives a reference case that corresponds to the current climate situation. The alternative cases show the socioeconomic impacts on grain production of climate change, indicated by projected changes in average temperatures in 2050 and 2100. The immediate impact on grain production is estimated based on assessments of the physical impacts on the growth of grains. The GRACE model then shows how these impacts penetrate further to the economic system before an estimate of the economic impacts is provided.

Table 1. Assumptions for alternative cases.

		Average temperature 2050 (or 2100)			
Scenarios	Reference	Output	Land	LandCD	LandLf
The reference year	2011	2011	2011	2011	2011
External shock	NA	The same physical impact on grain yield			
Trigger point in grain production	NA	Output	Land	Land	Land
Consumption function	Default (CES)	Default	Default	Cobb-Douglas	Leontief

The key assumptions in the alternative cases are listed in Table 1. All share the same assumptions related to the economic system. The reference case represents the 2011 economy, which is unaffected by climate change by assumption. The alternatives introduce the same physical damage of climate change on grain yields. What differs is the alternative production and demand structures described above. Climate change is represented by regional average temperature in 2050 and 2100. Following Wei et al. (2019), we use the average temperature under the Representative Concentration Pathway 8.5 (RCP8.5) scenario generated from an ensemble of 32 climate models participating in the Coupled Model Intercomparison Project - Phase 5 (CMIP5) (Taylor et al., 2012). The temperature change has a direct effect on grain yields, which is estimated in physical terms by a statistical model presented in Moore et al. (2017).

There are two ways to introduce the physical impact on grain yields in the economic system. One is to interpret the physical impact as the impact on the total output of grain. This means that a 5% physical damage on yields reduces the output of grain at the same rate of 5%. Hence, producers have no possibilities to adapt to climate change by changing the composition of input factors to limit the losses, such as if an unexpected flood driven by global warming destroys a part of the grain plants just before harvest. The "Output" alternative thereby represents a worst case showing the economic impacts of climate change.

The other way to integrate the physical impact is linking it to a reduction in the productivity of land. Then, the physical impact of climate change is considered isolated to the contributions to grain production from land. Other production factors, such as labor and capital, may compensate some of the losses related to the physical effect on the grain growth, e.g. by a change in production methods or intensified nutrition. The impacts in this case are shown in the "Land" alternative.

We also calculate the implications of flexibility in consumers' demand, expressed by the elasticities of substitution. The "LandCD" alternative replaces the default choice of CES demand-functions by Cobb-Douglas functions, which implies more flexibility and higher ability to adapt the consumption patterns (Fig. 3). The "LandLf" alternative applies Leontief functions to describe an inflexible consumption pattern, where substitution is disregarded. It must be added that the grain land is assumed given and unaffected by climate change in all alternatives.

We emphasize that the objective of this study is to show the uncertainties related to assessments of economic damages of climate change if based on deterministic estimates of physical effects. Hence, the study does not project future economic impacts of climate change. These will depend on many other factors, which add to the climatic changes, such as population growth, technological changes, capital accumulation, income distribution, and changes in lifestyle. All these factors may affect the capacity to adapt to the impacts of climate change in a future economy, and there are reasons to believe that the RCP8.5 gives an overly pessimistic projection of the future. The question is rather what role different socioeconomic factors play for assessments of the impacts of climate change.

3. Results and discussion

For each scenario, we calculate GDP at constant prices (GDP_CP), GDP deflated by global consumer price index (GDP_GCPI), and GDP deflated by national consumer price index (GDP_NCPI), respectively. According to Asheim and Wei (2009), GDP deflated by national consumer price index (CPI) considers the price change effect, and can be taken an indicator of the regional welfare.

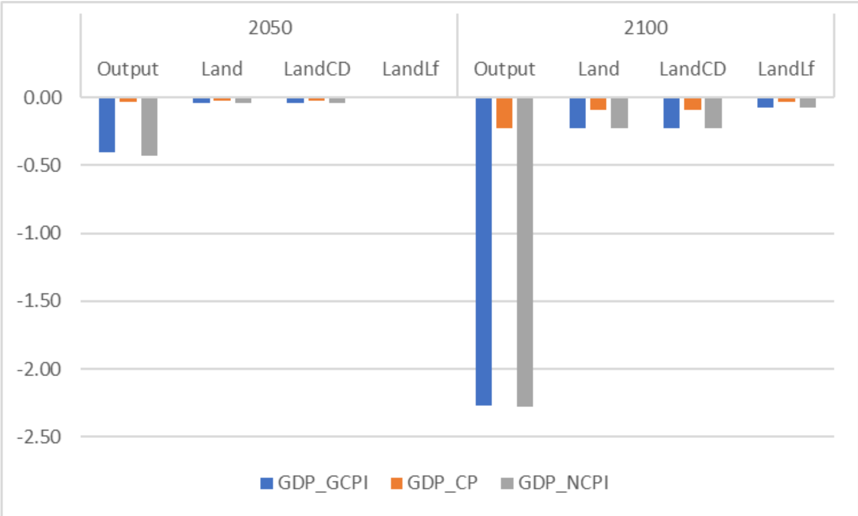

Fig. 4. Damages on global GDP due to impacts of climate change on production of main grains including wheat, rice and maize under various assumptions in 2050 and 2100. In the "Output" cases physical damage is assumed the same as damage on total production of grains in percentage. In other cases, physical damage is assumed the same as reduction in land productivity of grains in percentage where the "LandCD" cases further assume constant share of grains in total spending of households through a Cobb-Douglas consumption function and the "LandLf" cases assume constant ratio between grains and other goods in real terms through a Leontief consumption function.

3.1. *Price change effect*

Our results show that the price change effect is considerable for the estimated economic damage. As shown in Fig. 4, global GDP calculated by all the three approaches indicates the same direction of the climate change damage for each of the scenarios. GDP_GCPI and GDP_NCPI are identical at the global level although differ at national level (Fig. 5). Damages in terms of GDP_CP are much smaller than the other two in all cases (Fig. 4). The largest economic damage indicated by GDP_NCPI occurs in the 2100 "Output" alternative when the total grain production suffers the same as the physical damage in percentage terms by assumption, nearly ten times the damage indicated by the global GDP_CP. In other scenarios, the damages are modest although the global GDP_CPs are still much smaller than the other two indicators. These results imply that GDP_CP considerably underestimates the economic damages since the real price change effect is not included as done by the other two indicators.

The explanation to the large difference between the physical effects and the economic impacts is that grain products are largely necessary consumer goods and inelastic to a change in prices. Hence, damage on grain production leads to grain prices increased at a higher rate than the physical damage. Below we will focus on the GDP deflated by CPI rather than that at constant price.

3.2. *Adaptation*

As shown in Fig. 4, the “Output” alternative implies much stronger damage estimates than the “Land” interpretation. With climate change impacts corresponding to those in 2100, the economic damage in the “Output” alternative is 2.27% of GDP_NCPI (or 0.23% of GDP_CP) while that in the “Land” alternative is less than 0.23% of GDP_NCPI (or 0.09% of GDP_CP).

The explanation to the dramatic difference between the two alternatives is related to the possibilities for grain producers to adapt the production to avoid the negative physical damage of climate change. For example, if grain producers observe (or are warned about) negative impacts of climate change in advance, at least some of them will adjust their input to the production, e.g., by increasing the use of labor to offset the reduction in the productivity of land. If there is no way to limit the damages, the demand for labor in grain production will decrease and some of the workers in grain production will be employed in other sectors, and thereby limit the economic impacts at the regional level. The “Output” alternative excludes both adjustments. This alternative can, therefore, be considered as a worst-case estimate of the economic damage. The “Land” alternative includes both adjustments. It therefore gives much lower estimates of the economic damage and illustrates the considerable potential of adaptation measures of grain producers to mitigate the negative physical damage of climate change.

Notice that the adjustment cost of the adaptation measures is not included in the "Land" alternative, meaning that the reduced economic damage of these adaptation measures is somewhat overestimated in this alternative. The over-estimation then depends on whether the assumed adaptation measures are feasible in terms of both economic and technical terms. In any case, the potential benefit of the adaptation measures to reduce the economic damage as shown in our study would motivate the producers to take a large range of adaptation measures, as long as the adaptation cost is lower than the potential benefit from the avoided physical damage.

3.3. *Consumer preferences*

The assumptions related to consumer behavior may also contribute to mitigate the economic damage, especially under the Leontief demand assumption. In the 2100 climate scenario, the estimated economic damage under the Leontief demand assumption ("LandLf") is only 0.08% of GDP_NCPI while about 0.23% in the CES/CD demand assumption ("Land" or "LandCD"). Following the Leontief demand assumption, households cannot substitute grain products with other goods. Households will, therefore, spend a higher share of their income on grain products as the physical damage on grain production results in higher grain prices, compared to the cases of CES (or CD) demand assumption, where households can substitute gain products with other products. The relatively inelastic demand for grain products in households, on the one hand, motivate more grain production and supply. On the other hand, the demand for other products than grain is relatively reduced, allowing more resources to be used for grain production at relatively lower costs. Both channels result in less economic damage.

3.4. *Impacts on regional GDP*

Although all the alternatives imply negative economic impacts at the global level by GDP_GCPI and GDP_NCPI, there are positive impacts at the national level even in the worst “Output” case for 2100, as shown in Fig. 5. The figure also shows that GDP_GCPI underestimates the regional variations compared to GDP_NCPI. In some cases, GDP_GCPI indicates the wrong direction of the economic damage of a country since the impacts on prices are much stronger at the regional level than the global average.

As measured by GDP_NCPI, North American countries enjoy economic benefits rather than suffering economic damage as indicated by GDP_GCPI. More African countries suffer economic damage compared to that indicated by GDP_GCPI. Particularly, the economic damage in Ethiopia is 6% of GDP_NCPI rather than a benefit equal to 41% of GDP_GCPI, indicating how high prices at local level compared to the global average dramatically change the estimated economic impact.
As indicated by GDP_NCPI in Fig. 5, Most countries in Africa, Asia, and Latin America suffer economic damages, particularly India and North African countries. On the contrary, Canada, US, Australia, Argentina and several European countries enjoy certain economic benefits rather than damage.

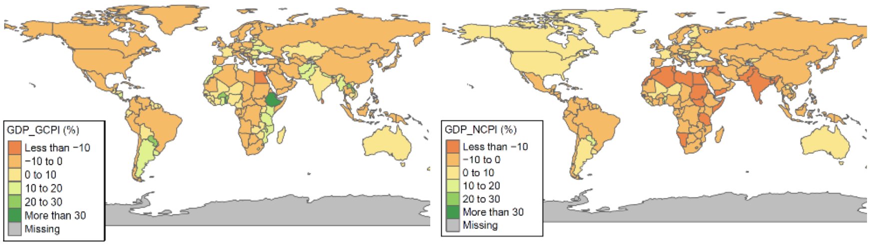

Fig. 5. Damages on national GDP at current price deflated by Global CPI (GDP_GCPI, in the left panel) and national CPI (GDP_NCPI, in the right panel) in the 2100 “Output” case (corresponding to average global warming in RCP8.5).

GDP_GCPI in this study can be taken an approximate of GDP calculated at purchasing power parities (PPP), when the basket of consumer goods is assumed to include all consumer goods in the world. It is well-known that such an indicator tends to overestimate the GDP of developing countries while being proper for developed countries since much more consumer goods in the PPP basket are from developed countries. According to Asheim and Wei (2009), GDP deflated at local CPI can serve as an indicator of welfare by taking price change effects into account to avoid counter-intuitive results. Hence, it is more plausible to use GDP_NCPI to indicate economic damage of climate change at national and regional levels.

3.5. *The choice of price index in IAMs*

GDP_CP is commonly used by statistical offices of a country and by researchers to measure economic damages associated with physical damages of climate change by assuming constant prices. The results above show problems in using this index because the effects of changes in relative prices are excluded. Climate change will typically imply different damages across sectors, which cause changes in relative prices across sectors. This study shows that changes in relative prices may modify the estimated economic damage considerably, which should not be omitted.

Most IAMs represent damages of climate change by the reduction in an economic aggregate, usually GDP. The question arises which GDP indictor should be used to measure the damages of climate change? As shown above, it depends on how the adaptation of producers and consumers is modelled in the IAMs. For example, if the utility is linked to an aggregate of consumption as the only independent variable, a CPI-deflated GDP should be used since in this case, the utility function does not capture effects of changes in relative prices among products. If the utility function is based on individual products as separate independent variables, the indicator calculated at constant price seems more plausible, since the effect of relative price changes is partially captured by the utility function although the adaptation of producers are still excluded. The results above show that the difference may be large.

If the aim is to compare economic damages across regions or countries, then GDP deflated by local CPI is recommended rather than GDP at PPP as illustrated by GDP_GCPI in this study, although GDP at PPP is widely adopted by international organizations such World Bank and International Monetary Fund, and many IAMs.

4. Conclusions

This chapter shows how alternative assumptions related to adaptation may modify estimates of the economic damage caused by climate change. The main message is the need to specify assumptions underlying estimates of the economic damages of climate change. We show that adaptation among economic agents implies that a physical effect of climate change on grain yield at 2.3 percent on the world scale in 2100 is modified to a reduction in costs between 0 and 2.3 percent, depending on the assumptions related to adaptation.

The economic impacts vary considerably across regions, however. In an average 2100 climate, the economic impacts due to a given physical impact on grain production range from -25% to 70% of the GDP at the regional level although only 0-2.3% at the global level. Not surprisingly, developing countries depending heavily on agriculture would suffer more economic damage of climate change. It is important for these countries to adjust industrial structure and develop diverse income sources to be better prepared for the much stronger regional damages of climate change than the global average.

A main reason why economic damages estimated at constant prices provide a poor indicator of the economic impacts is that the price effects are omitted. GDP deflated at local or regional CPI is the most plausible indicator of economic damage of climate change to measure the changes in local or regional welfare, although GDP at constant prices and PPP is widely adopted to represent economic damage of climate change in most IAMs and previous studies.

Since GDP is widely taken an indicator of economic growth, the choice of a price index in the GDP calculation is crucial to properly evaluate the climate change impact on economic growth, particularly in the cases of large changes in relative prices due to climate change. This is particularly important for developing countries as GDP at PPP tends to underestimate the climate damage on the local economy.

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