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ORIGINAL ARTICLE

How does climate change adaptation affect public budgets? Development of an assessment framework and a demonstration for Austria

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Abstract
Public adaptation to climate change affects government budgets directly on the expenditure side, but also indirectly via changes in the tax base and government consumption patterns. While such indirect effects have been analyzed intensively for mitigation policies, similarly detailed model-based frameworks and studies for adaptation policy are still missing. The objectives of the present paper are (i) to fill this gap by proposing a general modeling framework that allows for a comprehensive analysis of effects of adaptation on federal budgets, both on the expenditure and the revenue side, as well as of macroeconomic effects and (ii) to demonstrate its usefulness by applying this framework to the case of Austria. We find that public adaptation can lead to substantial positive macroeconomic effects on gross domestic product (GDP), welfare, and employment. The results are robust with respect to assumptions about the effectiveness of adaptation. Also, we demonstrate that it is essential for analysis to cover both the expenditure and revenue side, as overall government revenues can increase due to adaptation, offsetting additional direct public expenses for adaptation, thus increasing the budget balance. This is because of less severe climate change impacts and the corresponding lower payments for post-disaster relief and unemployment benefits as well as higher tax revenues. We thus strongly recommend making use of economy-wide modeling frameworks when planning for adaptation, as they shed light on the true costs and benefits of adaptation.

Keywords Climate change · Public adaptation · Indirect effects · Public budgets · Computable general equilibrium

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1 Introduction

In the last decade, national strategies for adaptation to climate change have been developed and implemented in numerous countries (Lesnikowski et al. 2015). It is widely held that, unlike mitigation, adaptation is a private good and therefore should be carried out by private actors (Tol 2005), whereas the role of the public sector is limited to providing the right incentives (Jones et al. 2013) and to correct for market failure (Osberghaus et al. 2010). However, the state owns public infrastructure, acts as service provider (e.g., by means of early warning systems), and plays a significant role as information broker (e.g., to coordinate extreme weather event preparedness and response) (Eakin and Patt 2011). This view is also supported when looking at national adaptation strategies, since a considerable share of adaptation is initiated by legislation, as well as financed and implemented by the public sector (Urwin and Jordan 2008; Biesbroek et al. 2010; McDonald 2011; Mees et al. 2012). Motivated by that, this paper takes a closer look at the direct and indirect consequences of public adaptation for federal budgets and develops a general modeling framework for quantification.

The public household is affected by climate change impacts and public adaptation through various channels (Bräuer et al. 2009; Bachner and Bednar-Friedl 2018). The impacts of climate change lead to direct costs for the public household, such as higher expenditures for disaster relief payments to private households or reconstruction of damaged public infrastructure. The benefit of adaptation is that it reduces some of these direct impact costs. Additionally, indirect effects on public budgets arise from both impacts and adaptation measures. This is because of changes in the tax base (e.g., due to changed economic activity and structure) and thus also tax revenues (cf. Lis and Nickel 2010; Schinko et al. 2016).

Public adaptation is usually integrated into the government's general practices to "climate proof" investment decisions and to mainstream adaptation into other policy fields (Bierbaum et al. 2013). However, the economic literature on adaptation until now has mostly ignored this complexity and modeled adaptation in a very stylized way, e.g., in the form of generic adaptation capital formation to identify an optimal adaptation level (de Bruin et al. 2009; Agrawala et al. 2011a, b; Bosello et al. 2013). For practical decision-making on public adaptation, however, these generalized insights from integrated assessment models are insufficient in that they do not allow for assessing the effects and usefulness of specific adaptation measures. This paper intends to fill this gap by developing a modeling framework that allows for a more detailed analysis of the economy-wide and budgetary effects of public adaptation.

As shown in the literature, climate change leads to significant losses in a broad range of economic sectors and of overall economic performance (Ciscar et al. 2011, 2012; Bosello et al. 2012; Sussman et al. 2014; Bosello and De Cian 2014; OECD 2015; Steininger et al. 2015; Dellink et al. 2017). Economy-wide effects can be much larger than direct impacts within sectors, due to indirect effects (Hallegatte et al. 2007). As argued above, adaptation also influences public budgets indirectly via sectoral spillovers and macroeconomic feedback effects, which affect the tax base and thereby alter the budget balance and the fiscal position of a country.

Yet while the fiscal implications of mitigation have been addressed (see Siegmeier et al. 2018 for a review), there is little known about the implications of public adaptation on government budgets. We argue that there is an essential difference between mitigation and adaptation, which requires a separate and detailed analysis to better understand the effects of adaptation on government budgets. While mitigation policies have the potential to generate revenues (e.g., via carbon taxes), the direct effects of adaptation arise mostly on the expenditure side. Mitigation therefore allows for cutting distortionary taxes or increasing expenditures (such as on carbon-free technologies) but financing adaptation requires either cutting other public expenditures or raising taxes in order to ensure sustainable government finances.

In general, the literature on budgetary implications of climate change impacts and adaptation is scarce. Regarding the direct consequences of climate change impacts for public budgets, some papers describe effects qualitatively and provide empirical estimates for changes in expenditures (Bräuer et al. 2009; Margulis and Narain 2010; Osberghaus and Reif 2010; Jones et al. 2013; Gilmore and St. Clair 2018). Complementary to these are econometric studies that estimate the effects of climate variability and extreme weather events on public finances (Lis and Nickel 2010; Ouattara and Strobl 2013; Melecky and Raddatz 2015; Leppänen et al. 2015); however, they are limited to direct effects on public expenditures, disregarding indirect effects. Indirect effects to public budgets have been analyzed for climate change impacts—but not for public adaptation—in a computable general equilibrium framework by Bachner and Bednar-Friedl (2018).

Since the quantification of adaptation-induced effects on public budgets is still underdeveloped, the objectives of this paper are as follows. First, we present a general modeling framework that allows for a comprehensive analysis of effects of adaptation on federal budgets, both on the expenditure and the revenue side, as well as of macroeconomic effects. The proposed framework can be applied to any country or region, even though adaptation is very location specific. Second, we demonstrate its usefulness by applying this framework to the case of Austria.

2 Modeling framework

2.1 Scenarios and conceptual model

In the modeling framework, we distinguish between three types of scenarios for 2050: (i) the Baseline scenario, describing general socioeconomic development; (ii) the Impact scenario, which adds climate change impacts to the Baseline; and (iii) the Adaptation scenario, which adds adaptation measures to the Impact scenario, reducing impacts but also inducing new costs for adaptation. By comparing these scenarios to each other, we are able isolate effects of climate change impacts (Impact versus Baseline scenario) and of adaptation (Adaptation versus Impact scenario). In the Impact and Adaptation scenarios, the federal government's budget is affected both on the expenditure and on the revenue side, however, in different ways.

Figure 1 conceptually illustrates the effects of climate change impacts and adaptation on government expenditures. In the Baseline scenario, expenditures consist of four major items: (i) non-climate-related government consumption of goods and services (including wages of public workers), (ii) expenditures on reconstruction (investment) and relief payments for damages caused by extreme weather events, (iii) unemployment benefits to be paid as social security, and (iv) other transfers to households. The first two items represent general government consumption.

With climate change, i.e., in the Impact scenario, the composition, and the level of government expenditures change. As a direct effect of climate change, reconstruction and relief payments increase due to higher damages, but several indirect effects also emerge. Depending on the sectoral and macroeconomic impact of climate change, tax revenues change. As most macroeconomic climate change impact studies find a negative effect on general economic activity (GDP), it is plausible to assume a loss in tax revenues, reducing the means

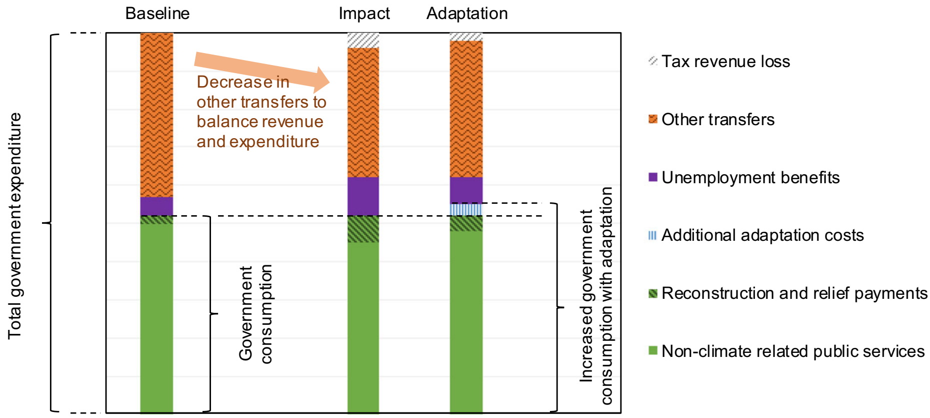

Fig. 1 Conceptual model of effects of climate change impacts and adaptation on government expenditures. Magnitudes of expenditure categories in the Baseline are set to reflect the EU-wide public expenditure structures (EUROSTAT 2018). The effects in the Impact and Adaptation scenarios are depicted exaggeratedly for illustrative purposes

for expenditure but also increasing the need for unemployment benefits (lower economic activity implies higher unemployment). To ensure no increase of the public deficit, government expenditures need to be re-distributed within the now smaller total available budget. To achieve this aim, two adjustments are possible: cutting either transfers to households or other non-climate-related government consumption, or both. It is plausible to assume for many countries that the level of government consumption is fixed by multi-annual budgeting rules. As a consequence, the total level of government consumption would remain constant but is restructured towards more disaster relief payments and less other government consumption, leaving other transfers to balance revenue and expenditure (as indicated in Fig. 1).

In the Adaptation scenario, direct and indirect effects again impact government expenditures. The direct effect is caused by additional public adaptation costs. We assume that multi-annual budgeting accounts for public (planned) adaptation and thus adaptation increases total government consumption. The indirect effects arise again via macroeconomic feedback effects. Impacts are reduced by adaptation and economic activity increases; therefore, total tax revenue losses are less severe compared to the Impact scenario. Since reconstruction and relief payments are smaller with adaptation, other government consumption is expanded as compared to the Impact scenario (however, not reaching the Baseline level due to residual damages also in the Adaptation scenario). Due to higher employment, which can be caused by both higher economic activity and typically high labor intensity of government consumption, expenditure for unemployment benefits is lower compared to the Impact scenario. Depending on the size of the of tax revenue loss and the effect on employment, other transfers can then either be increased (as shown in Fig. 1) or cut to keep the balance between revenue and expenditure.

In this context, it is important to consider government budgeting rules. Many countries have committed themselves to avoiding excessive deficits and pursuing fiscal sustainability. For instance, the European Stability and Growth Pact (European Union 2008, Art. 121 and 126) requires that all member states keep the government deficit below 3% of GDP, with government debt not exceeding 60% of GDP. In our analysis and as illustrated in Fig. 1, we therefore assume that government consumption in the Impact scenario is fixed at the Baseline level, and that this fixation is established via adjustments in transfers to households.

2.2 Quantitative model and analysis

To analyze and quantify the economy-wide and budgetary effects of climate change impacts and adaptation, including indirect effects, we suggest a stepwise approach. Step 1 aims to isolate adaptation (relevant) expenditures from total public expenditures. To do so, budget and government expenditure reports need to be collected and screened for adaptation-relevant keywords that indicate adaptation actions. The selection of adaptation-relevant keywords can be supported by reviewing national adaptation strategies, implementation plans, or submissions to national climate assessments (Bierbaum et al. 2013). After the identification of adaptation-relevant budgetary items, it is necessary to narrow down adaptation-relevant expenditure to adaptation expenditure. This can be done by applying shares, which is not an easy endeavor, especially when adaptation is not the primary objective but a co-benefit (Gilmore and St. Clair 2018). Experts in ministerial departments often have valuable knowledge concerning the exact purposes of budgetary items and can thus aid in estimating the shares of adaptation. Alternatively, the OECD Development Assistance Committee (2016) and the European Commission (2016) developed a set of attribution rules that indicate which share of total costs should be assigned to adaptation expenditures for specific budgetary items.

In step 2, starting from these current expenditures, a realistic adaptation pathway is co-developed for the future (e.g., 2050) together with experts and stakeholders, ideally from key ministries engaged in adaptation action as well as finance ministries. Often, however, the capacity and the willingness to engage in such a process is limited. An alternative procedure is therefore to develop this pathway based on general recommendations from the literature, such as the concept of adaptation phasing (Watkiss et al. 2015). To deal with uncertainties and limits to specific adaptation actions, such a pathway should not be regarded as set in stone, but rather be regularly re-assessed in an iterative manner, such as is proposed by Haasnoot et al. (2013) who present the approach of "dynamic adaptive policy pathways."

In step 3, the direct and indirect consequences of the adaptation pathway for the public budget are analyzed. In principle, several approaches could be used to assess these impacts: projections based on econometric models (Lis and Nickel 2010; Ouattara and Strobl 2013; Leppänen et al. 2015), government financial risk simulation models like CATSIM (Hochrainer-Stigler et al. 2014b), or multi-sectoral computable general equilibrium (CGE) models. Econometric models are based on time-series or panel data, which allows for an assessment of budgetary effects over time, but they usually neglect macroeconomic feedback effects that alter the tax base. Financial risk simulation models are particularly adept at studying loss distributions and effects on budgetary gaps, but the representation of the overall economy is highly aggregated. CGE models have the advantage of capturing these macroeconomic and cross-sectoral feedback effects as they distinguish between different economic sectors and agents (Fisher-Vanden et al. 2013) and also capture the revenue side. However, CGE models are more suitable for capturing long-term equilibrium effects, not short-term effects.

3 Model implementation and data

In the following analysis, we apply the described modeling framework to the case of Austria. We focus on the impact fields with the highest federal budgetary importance and with potentially strong impacts for the Austrian economy (Bednar-Friedl et al. 2017): Agriculture, Forestry, and Catastrophe Management (including protection from natural hazards).

Agriculture is heavily subsidized and thus public resources indirectly fund adaptation in this sector. Forestry is of high relevance since its expected contribution to macroeconomic damages is relatively high (− 0.8% GDP loss in 2050; Bachner et al. 2015). In addition, the government owns a large share of the protection forests in Austria. Catastrophe Management is closely connected to the public domain, since the Austrian disaster fund is fully financed out of tax revenue (Schinko et al. 2016). Our scenarios are in line with the RCP-SSP framework, which is standard in climate change research. Representative Concentration Pathways (RCPs) describe different global emission trajectories, while Shared Socioeconomic Pathways (SSPs) describe different narratives for socioeconomic development. By combining RCPs and SSPs, different states of the world emerge in which climate change impacts materialize (Moss et al. 2010; O'Neill et al. 2014). For the Baseline scenario, we choose a "middle-of-the-road" shared socioeconomic pathway (SSP2; O'Neill et al. 2014). For details on the Baseline calibration, see Appendix A.1.

3.1 Current and future public adaptation at the federal level in Austria

To identify current federal expenditures on public adaptation (step 1), we screened the federal budget in the base year (2016) for adaptation-relevant expenditure items and categorized them into gray, green, or soft measures (see Appendix A.2 for details). Soft measures comprise information measures such as early warning systems; gray measures are comprised of structural protection, for example, flood protection dams; and green measures are ecosystem-based measures such as natural flood retention areas or forest management. Additionally, we include a separate category for research and development (R&D).

The result of the screening is shown in the base year (2016) in Fig. 2, with the largest expenditure items being gray measures in the Catastrophe Management impact field (CATM, € 471 million p.a.) and green measures in the Agriculture impact field (AGRI, € 257 million p.a.). Expenditures on soft measures and R&D play only a minor role. In total, current annual adaptation-relevant expenditures sum up to € 908 million (15% of the screened budgetary subdivisions).

Starting from 2016, we co-developed[1] an indicative adaptation expenditure pathway until 2050 (step 2). This pathway combines expert judgment on the additional resources needed for single adaptation measures, on limits to further increase gray adaptation measures and international recommendations on the phasing of gray, green, and soft measures (Watkiss et al. 2015). For the Baseline expenditure path, the growth rate of the mid-term budget forecast for the Federal State of Austria is used (1.65% annually; assuming the same shares as in 2016) (BMF 2015). Figure 2 illustrates the pathway by type of adaptation measure and impact field in which adaptation is carried out and funded. On average, expenditures of this indicative Adaptation scenario rise by 3% p.a. over the period 2016–2050, which is above the 1.65% assumed in the Baseline. For details on this co-developed pathway, see Appendix A.2.

3.2 Macroeconomic model and scenario implementation

For the macroeconomic analysis (step 3), we use a single-country, comparative static CGE model of Austria (Bachner et al. 2015; Steininger et al. 2016; Bachner and Bednar-Friedl

[1] This co-development took place within the research project PACINAS (http://anpassung.ccca.at/pacinas/en/), funded by the Austrian Climate and Energy Fund.

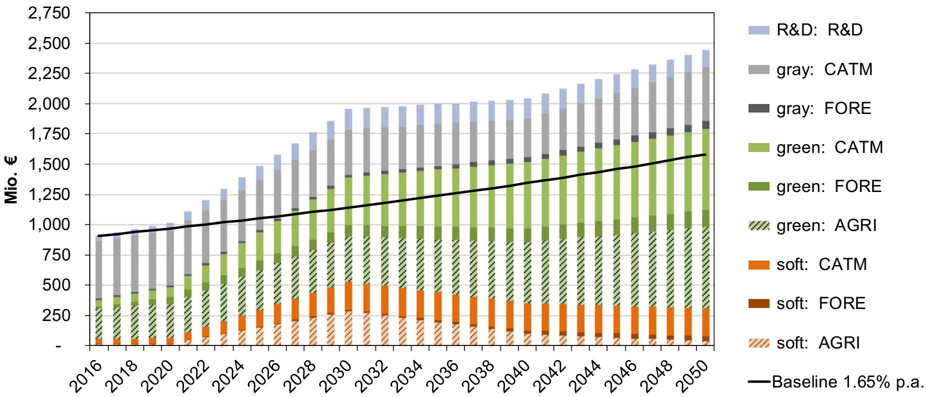

Fig. 2 Indicative adaptation pathway for the Austrian federal budget until 2050 (R&D= Research and Development; CATM= Catastrophe Management; FORE= Forestry; AGRI= Agriculture)

2018). The model covers 40 economic sectors and one representative private household, which is endowed with labor and capital. The respective factor income is spent for consumption or is saved. In addition, there is a public household providing public services, financed by the following taxes: sales taxes on output, tax on capital gains, labor tax, value added tax, and export tax. All tax rates are fixed, thus determining flexible government income, which in turn gives the total amount of available public budget to be spent. The model includes classical unemployment and international trade is depicted via the Armington (1969) assumption, where domestic goods are imperfect substitutes for imports. The foreign balance is fixed at the share of the model's benchmark year (2008). Regarding the development of the budget deficit, we assume a constant deficit-to-GDP ratio, which is an empirically well-supported assumption for the structural deficit and also in accordance with the criteria of the EU Stability and Growth Pact. For more details and the algebraic formulation, see Bachner (2017).

3.2.1 Implementation of the impact scenario

Climate change is implemented as average changes for the future 30-year climatic period 2036–2065 (i.e., 2050), relative to the average of the reference climatic period 1981–2010. Specifically, we use the SRES (Special Report on Emissions Scenarios) A1B emissions scenario (Nakićenović and Swart 2000), which corresponds to the RCP6.0 scenario with + 2.5 °C global mean temperature by the end of the century (Knutti and Sedláček 2013). For details, see Appendix A.1.

Climate change impacts are implemented in ten impact fields. For each of these fields, different types of impacts are quantified using a range of (bio)physical models. These impacts are implemented into the macroeconomic CGE model by (i) changes in production cost structures (e.g., a different production process in Agriculture), (ii) changes in productivity (e.g., yield changes in Agriculture and Forestry), (iii) changes in investments (e.g., reconstruction of infrastructure after flood events), and/or (iv) changes in public expenditures (e.g., more post-disaster relief payments in Catastrophe Management). Table 1 summarizes the impacts for the three impact fields under consideration (for all other, see Appendix A.1). As explained in Section 2, to keep expenditures on public service provision (i.e., government consumption) at the same level as in the Baseline scenario, we assume in the Impact scenario that transfers to private households are adjusted accordingly.

Table 1 Summary of impacts and (bio-)physical impact models

Impact field	Impacts	(Bio)physical impact model used for quantifying impact
Agriculture	Crop productivity of main crops (grain maize, winter wheat, winter rape, soybean, temporary grassland) and grassland due to changes in temperature and precipitation	Regression analysis (Mitter et al. 2015b) based on simulations with the biophysical process model EPIC (Izaurralde et al. 2006) and the farm optimization model PASMA (Schmid 2004)
Forestry	Biomass productivity in commercial production forests due to changed precipitation and temperature, bark beetle disturbances on productivity of commercial forests and protection functionality of protection forests	Estimation of productivity changes with forestry revenue model PICUS 3G (Schörghuber et al. 2010) and of damages from spruce bark beetles with FISCEN scenario model (Seidl et al. 2009, 2011); impact of bark beetle disturbances on protection functionality based on expert guess (Lexer et al. 2015)
Catastrophe Management	Building damages due to riverine floods	Simulation of riverine flooding damages in a hybrid convolution approach (Hochrainer-Stigler et al. 2014a) (which builds on results of the LISFLOOD model, the Climate Cost project (Feyen and Watkiss 2011; Rojas et al. 2013) and on the Adam Cost project (Kundzewicz et al. 2010; Lugeri et al. 2010)

3.2.2 Implementation of the adaptation scenario

The Adaptation scenario builds on the Impact scenario but additionally incorporates direct costs and benefits (i.e., avoided impacts) of public adaptation measures in the three impact fields under consideration. Adaptation costs are divided into operating costs (e.g., labor costs, contracting to spatial planning bureaus, maintenance costs for public infrastructure) and investment costs. Changes in sectoral operating costs are modeled as shifts within the production cost structures while holding unit costs constant (but having a different composition of costs). Changes in government consumption patterns and levels (which are also a part of operating costs) are implemented as additional consumption, financed via cuts in transfers to the private household (and hence reduced private consumption). Accumulation effects of annual investment changes are accounted for, resulting in a changed capital stock in 2050 with associated changed annual capital costs (depreciation). Note that the deployed CGE model is not dynamic but comparative static. The development of the capital stock is therefore no explicit part of the model but accounted for when developing the adaptation pathway. Changes in investment are financed via changed savings and thus corresponding changes in private consumption. Table 3 shows how the indicative adaptation pathway (Fig. 2) translates into annual changes of sectoral costs as well as changes in government consumption (annualized for 2050, relative to the Impact scenario). For details on the calculations, see Appendix A.2 (Table 2).

The benefit of adaptation is avoided damage. The respective assumptions on the effectiveness of different measures (i.e., by how much damages can be reduced) are summarized in Table 3. Following the literature and expert estimates, we assume that agricultural crop yields can be increased by 10% and damages in Forestry can be reduced by 30–40%. For the Catastrophe Management impact field (flood protection), we use benefit-cost ratios to quantify effectiveness. For the Adaptation scenario, we use mean values for a central simulation run,

Table 2 Translation of the adaptation path into annual cost vectors for modeled sectors (agriculture, forestry, water) and agents in 2050 (in million €)

	Agriculture	Forestry	Water	Government consumption	Aggregate investment
Labor	+ 25	+ 69	+ 48		
Capital (incl. land)		+ 126	+ 32		
Research and development				+ 60	
Civil engineering and planning				+ 165	
Machinery	+ 213	+ 102			
Construction (Investment)		+ 39	− 45		− 6
Total	+ 239	+ 336	+ 93	+ 226	− 6

but also provide results for a bandwidth (lower and upper bound) to address uncertainty. For details, see Appendix A.3.

Finally, note that also in the Adaptation scenario, we assume that expenditures of public service provision are maintained at the Baseline level by adjusting transfers to households. In addition, however, we allow for increased consumption for adaptation measures (as indicated in Fig. 1).

4 Results

4.1 Economy-wide effects of public adaptation

In 2050, climate change-induced annual GDP losses in the Impact scenario are − 0.15% relative to the Baseline (see Appendix A.4 for the detailed results). In the mean Adaptation

Table 3 Description, assumption, and sources of effectiveness of adaptation measures in the impact fields CATM (Catastrophe Management), AGRI (Agriculture), and FORE (Forestry)

Impact field	Adaptation measure/purpose	[lower] mean [upper] value for analysis	Description of unit of measurement	Source
CATM	Soft flood protection measures	[1.5] 9.2 [10]	Benefit/cost-ratio	(Kuik et al. 2016)
	Green flood protection measures	[1.2] 1.8 [4.3]	Lower bound: 10th percentile	
	Gray flood protection measures	[1] 3.9 [7.7]	Upper bound: 90th percentile	
AGRI	Change in agricultural crop management practices	[5%] 10% [15%]	Yield increase potential in response to adaptation measures	(Mitter et al. 2015a; Schönhart et al. 2016)
FORE	Educational measures against bark beetles; more intensive tending of forests; better infrastructure in forests	[20%] 32% [45%]	Damage reduction of damages to protective forest	(Kolström et al. 2011; Lexer 2017)
	Educational measures against bark beetles; more intensive tending of forests; better infrastructure in forests	[35%] 40% [45%]	Damage reduction of damages to commercial timberland	
	Genetics: Better usage of autochthonous species to increase resilience of forests	[0%] 0.03% [0.03%]	Reduction in timber growth loss	

scenario, these losses can be reduced by public adaptation to only −0.06%. To put it differently, adaptation leads to a net benefit of +0.09%-points of annual GDP compared to not adapting; however, there is still a residual loss when compared to the Baseline scenario with no climate change. This benefit from adaptation is illustrated in Fig. 3 (black diamonds). The reasons for this GDP effect are twofold: First, there are positive effects from adaptation-specific productivity gains (Agriculture) as well as positive employment effects. Second, there are reductions of direct and indirect climate change impacts from the Forestry and Catastrophe Management impact fields.

The welfare loss, measured as Hicksian equivalent variation, in the Impact scenario is −0.48% (again, see Appendix A.4 for the detailed results), which in the Adaptation scenario can be reduced to −0.27%. Public adaptation therefore creates a welfare benefit of +0.2%-points (Fig. 3). Note that the size of the welfare effect is larger than the GDP effect in the Impact and the Adaptation scenarios. This is because some consumption expenditure is "forced" to shift from generic (welfare enhancing) consumption to the renewal of destroyed assets. This shift however only restores the original state (e.g., prior to an extreme event) and is thus reducing other consumption possibilities (i.e., welfare). In contrast, the GDP effect is neutral to this re-distribution within the consumption structure.

Figure 3 furthermore shows how the total benefit of public adaptation on GDP, welfare, and unemployment is distributed across impact fields. We find that the positive effect of adaptation on GDP arises from Agriculture (due to productivity gains) and Forestry (especially due to the

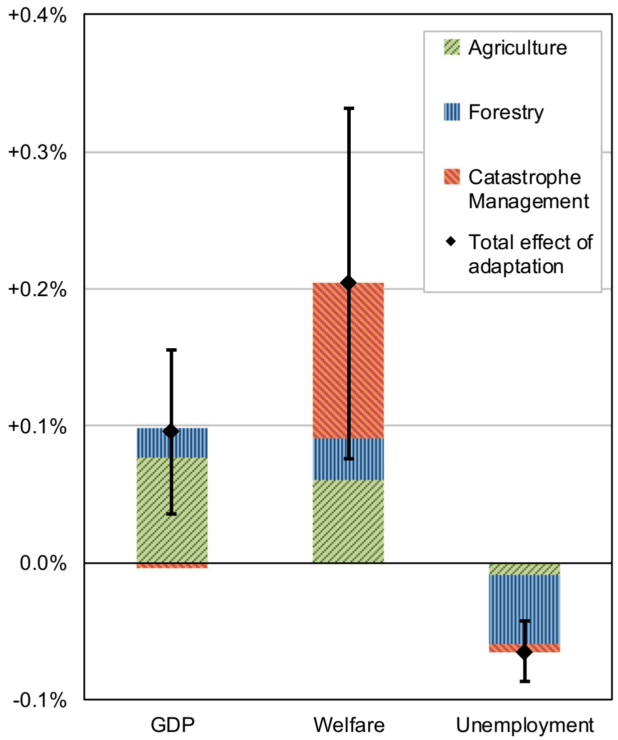

Fig. 3 Effects of adaptation on GDP, welfare, and unemployment for 2050 (Adaptation scenario relative to Impact scenario, given in percentage point differences), distinguished by impact field and in total. Error bars indicate different assumptions on effectiveness of adaptation measures to reduce climate change impacts

reduction of damages to protection forests). For Catastrophe Management, the shift from a capital-intensive to a more labor-intensive structure results in only a marginal GDP effect from adaptation, as the effects offset each other. Substantial positive effects on welfare emerge from reduced damage costs in Catastrophe Management and the associated reduction in forced consumption. A positive contribution of adaptation to welfare also arises from Agriculture, due to productivity gains and the moderating effect on food prices. In Forestry, we find positive welfare effects primarily caused by the reduced damage to protection forests and thus more public finances available to increase transfers to households. We also see that unemployment is reduced by adaptation in all impact fields, which is driven by the focus on green and soft adaptation as well as by higher expenditures for labor-intensive government consumption. Regarding the uncertainty of effectiveness of adaptation (see the error bars in Fig. 3), we find that the results are robust in terms of the direction of the effects.

4.2 Effects of public adaptation on government budgets

Beginning with a description of results on the revenue side of the budget, the effect of adaptation on the main tax revenue categories is shown in Fig. 4a, which compares the Adaptation and Impact scenario in absolute terms (and with %-points differences on the secondary axis). With adaptation, tax revenues increase for labor and production taxes (due to higher economic activity and employment), but decline in value added tax, since there is less forced consumption for restoring damaged assets and because the government needs to finance its adaptation expenditure (which is taxed at lower rates than private consumption).

Figure 4b shows the expenditure side (again, Adaptation compared to the Impact scenario). In the Adaptation scenario, relief payments to households can be reduced substantially; thus, non-climate-related government consumption can be increased. However, direct public adaptation expenditures amount to additional € 219 million (0.1% of total expenditure). Moreover, due to higher tax revenues and less payments for unemployment benefits, transfers to households can be increased in the Adaptation scenario. Only when the effectiveness of adaptation is very low, transfers to households need to be reduced to ensure stability of government consumption (service provision). Eventually, the analysis allows for matching numerical assessment to the conceptual model from Fig. 1, which is presented in Figure A.1.

Finally, Fig. 4 also shows the decomposition of the effects of adaptation across the three impact fields. On the revenue side, we find that the relative contribution to higher labor taxes is particularly strong for public adaptation in Forestry, as forest management is comparatively labor-intensive. Revenues from value-added tax decline, however, as a result of adaptation in Catastrophe Management, due to less forced consumption, leading to a slightly negative contribution of adaptation in that regard. On the expenditure side, we find a significant reduction in relief payments to private households from Catastrophe Management in the form of structural flood protection. Adaptation expenditures increase particularly due to adaptation in Catastrophe Management and Forestry, because both sectors are recipients of subsidies for, e.g., ensuring the function of protection forests.[2]

[2] Note that the effect of adaptation in Catastrophe Management to transfers would be negative when performed in isolation (since there is no large positive effect from these measures on employment and GDP), as expensive structural measures need to be financed by cuts in transfers. However, the overall positive contribution of adaptation in Forestry and Agriculture more than compensates for these transfer cuts.

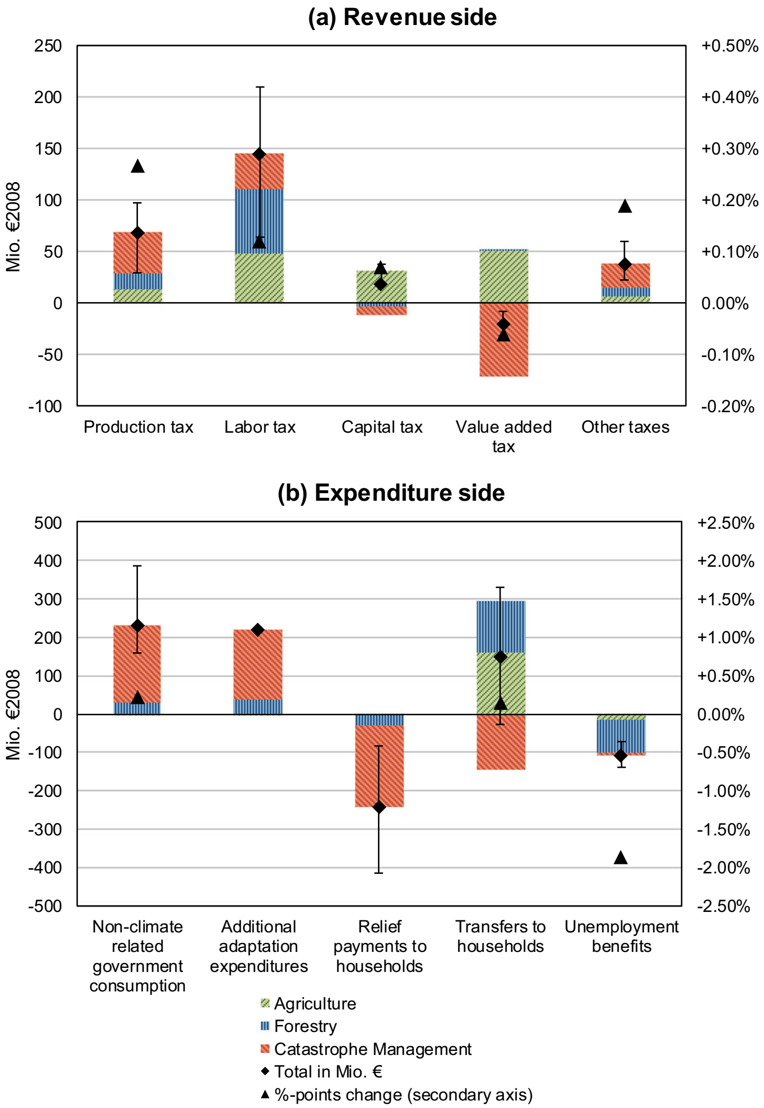

Fig. 4 Decomposition of effects of public adaptation on tax revenue (**a**) and public expenditure (**b**) for the three adaptation fields for 2050 (Adaptation scenario relative to Impact scenario). Diamonds show absolute total effect and triangles show percentage point differences between Adaptation and Impact scenarios (secondary axis). Error bars indicate different assumptions on effectiveness of adaptation measures to reduce climate change impacts. Note that %-point changes are not shown for relief payments (− 81%) and for additional adaptation expenditures (which would be infinite when calculated since its value in the Baseline and Impact scenario would be zero)

5 Discussion and conclusions

In the first part of the paper, we presented a modeling framework that allows for a more detailed analysis of the budgetary effects of public adaptation to climate change, taking account of economy-wide feedback effects. Until now, such analyses have not been available, but are urgently needed for informed policy making, including the phasing and prioritization of adaptation measures. The proposed framework can be applied to any country or region; however, it involves considerable effort with respect to data preparation and stakeholder consultation, as adaptation is often integrated in general public sector activities.

In the second part of the paper, we demonstrated the usefulness of the proposed framework for the case of Austria. We show that public adaptation already involves considerable costs for the federal budget (15% of the pre-selected budget is adaptation-relevant). These costs are likely to rise in the future, due to ongoing climate change but also due to re-investment cycles in public infrastructure. For requirements of robust government finances, these higher expenditures on adaptation require that other public expenditures are reduced accordingly; however, the extent depends on how tax revenues and social benefit payments are affected by adaptation. To also capture these indirect effects of public adaptation, we investigated how public adaptation in Agriculture, Forestry, and Catastrophe Management affects GDP, welfare, and unemployment. The first key lesson learned is that due to positive effects on GDP, welfare and employment, public adaptation can lead to a net benefit from a macroeconomic perspective. While the effectiveness of adaptation measures to reduce climate change impacts is still subject to uncertainty, we find that the direction of our results is highly robust with regard to different assumptions on the effectiveness of adaptation measures.

When looking more closely at the government budget, we find that public adaptation has the potential to increase government revenues (in total and for all categories except valued added tax) because of higher economic activity as compared to a scenario with only the impacts of climate change. On the expenditure side, public adaptation leads to a partial redistribution of government expenditures towards adaptation but also to a reduced need for disaster relief payments. Moreover, reduced unemployment translates into less unemployment payments. The effect on transfers tends to be positive but can be slightly negative when adaptation measures' effectiveness is very low. Overall, the second key lesson learned is that it is possible that the positive indirect effects of public adaptation outweigh the direct public costs of adaptation, with a resulting increase in the overall government budget, another insight offered by the proposed framework.

Regarding global adaptation strategy recommendations, our findings imply that adaptation assessments should take a comprehensive perspective based on quantitative economic modeling, and include both the revenue and expenditure side as well as indirect effects. Computable general equilibrium models are very useful in that respect. As we have shown, the macroeconomic benefits of adaptation can outweigh the costs, because of indirect effects, e.g., on economic activity in other sectors and employment. Such effects may turn cost-benefit assessments in favor for adaptation measures with high direct costs, but strong positive indirect effects. This is the case, e.g., for labor-intensive green adaptation measures.

We also demonstrate the advantage of a close collaboration between academia and administration (especially from finance and treasury), in order to develop realistic and policy-compatible adaptation pathways. Such a collaboration also raises awareness within the policy domain and enhances the mainstreaming of climate change adaptation across the board.

Regarding the generalizability of our results for other countries, we conclude the following. For countries with (i) similar budgetary structures as well as (ii) similar patterns of impacts (as in Austria), the revealed mechanisms can lead to the same qualitative effects. Regarding the first similarity—the budgetary structure—we know that across EU member states, these structures are very homogenous (EUROSTAT 2018). Among OECD countries, the variations are larger, yet the dominant revenue and expenditure categories are still the same (OECD 2018a, b). Similar impact patterns relate to high damages from flooding and forestry (loss of ecosystem services) and moderate positive effects in Agriculture. As this is the case for many developed regions and industrialized countries, the qualitative insights and mechanisms as obtained from our case might also carry over to many other OECD and EU countries.

As this paper is the first to analyze not only the direct but also the indirect effects of public adaptation on government budgets, limitations and several directions for future research should naturally be discussed. First, a better understanding of how the effectiveness of adaptation can change over time is definitely needed. Second, while we develop an indicative and plausible adaptation pathway together with professionals from relevant government departments, several alternative adaptation pathways could be developed and compared with regard to their macroeconomic and budgetary consequences. Third, it would be interesting to investigate in more detail how different budgetary rules, such as flexible tax rates or additional foreign debt, interact with public adaptation spending, an exercise which would require a more dynamic modeling setting.

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References

Agrawala S, Bosello F, Carraro C et al (2011a) Adapting to climate change: costs, benefits, and modelling approaches. Int Rev Environ Resour Econ 5:245–284. https://doi.org/10.1561/101.00000043

Agrawala S, Bosello F, Carraro C et al (2011b) Plan or react? Analysis of adaptation costs and benefits using integrated assessment models. Clim Chang Econ 02:175–208. https://doi.org/10.1142/S2010007811000267

Armington PS (1969) A theory of demand for products distinguished by place of production (Une theorie de la demande de produits differencies d'apres leur origine) (Una teoria de la demanda de productos distinguiendolos segun el lugar de produccion). Staff Papers - International Monetary Fund 16:159. https://doi.org/10.2307/3866403

Bachner G (2017) Assessing the economy-wide effects of climate change adaptation options of land transport systems in Austria. Reg Environ Chang 17:929–940. https://doi.org/10.1007/s10113-016-1089-x

Bachner G, Bednar-Friedl B (2018) The effects of climate change impacts on public budgets and implications of fiscal counterbalancing instruments. Environ Model Assess. https://doi.org/10.1007/s10666-018-9617-3

Bachner G, Bednar-Friedl B, Nabernegg S, Steininger KW (2015) Macroeconomic evaluation of climate change in Austria: a comparison across impact fields and total effects. In: Steininger KW, König M, Bednar-Friedl B et al (eds) Economic evaluation of climate change impacts: development of a cross-sectoral framework and results for Austria. Springer, Berlin, pp 415–440

Bednar-Friedl B, Knittel N, Leitner M, Bachner G (2017) The cost of climate change adaptation for the Austrian Federal Budget. PACINAS Working Paper #04. http://anpassung.ccca.at/pacinas/en/ergebnisse/. Accessed 1 Jun 2018

Bierbaum R, Smith JB, Lee A et al (2013) A comprehensive review of climate adaptation in the United States: more than before, but less than needed. Mitig Adapt Strateg Glob Chang 18:361–406. https://doi.org/10.1007/s11027-012-9423-1

Biesbroek GR, Swart RJ, Carter TR et al (2010) Europe adapts to climate change: comparing national adaptation strategies. Glob Environ Chang 20:440–450. https://doi.org/10.1016/j.gloenvcha.2010.03.005

BMF (2015) Strategiebericht zum Bundesfinanzrahmengesetz 2016-2019 gemäß § 14 BHG 2013. Bundesministerium für Finanzen, Vienna

Bosello F, De Cian E (2014) Climate change, sea level rise, and coastal disasters. A review of modeling practices. Energy Econ 46:593–605. https://doi.org/10.1016/j.eneco.2013.09.002

Bosello F, Nicholls RJ, Richards J et al (2012) Economic impacts of climate change in Europe: sea-level rise. Clim Chang 112:63–81. https://doi.org/10.1007/s10584-011-0340-1

Bosello F, Carraro C, De Cian E (2013) Adaptation can help mitigation: an integrated approach to post-2012 climate policy. Environ Dev Econ 18:270–290. https://doi.org/10.1017/S1355770X13000132

Bräuer I, Umpfenbach K, Blobel D et al (2009) Klimawandel: Welche Belastungen entstehen für die Tragfähigkeit der Öffentlichen Finanzen? Endbericht, Ecologic Institute, Berlin

Ciscar J-C, Iglesias A, Feyen L et al (2011) Physical and economic consequences of climate change in Europe. Proc Natl Acad Sci U S A 108:2678–2683. https://doi.org/10.1073/pnas.1011612108

Ciscar J-C, Szabó L, van Regemorter D, Soria A (2012) The integration of PESETA sectoral economic impacts into the GEM-E3 Europe model: methodology and results. Clim Chang 112:127–142. https://doi.org/10.1007/s10584-011-0343-y

de Bruin KC, Dellink RB, Tol RSJ (2009) AD-DICE: an implementation of adaptation in the DICE model. Clim Chang 95:63–81. https://doi.org/10.1007/s10584-008-9535-5

Dellink R, Lanzi E, Chateau J (2017) The sectoral and regional economic consequences of climate change to 2060. Environ Resour Econ. https://doi.org/10.1007/s10640-017-0197-5

Eakin HC, Patt A (2011) Are adaptation studies effective, and what can enhance their practical impact? WIREs Climate Change 2:141–153

European Commission (2016) Tracking climate expenditures. The common methodology for tracking and monitoring climate expenditure under the European Structural and Investment Funds (2014–2020). Brussels, Belgium

European Union (2008) Consolidated Version of the Treaty on the Functioning of the European Union

EUROSTAT (2018) Government finance statistics - Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php/Government_finance_statistics. Accessed 26 Nov 2018

Feyen L, Watkiss P (2011). The impacts and economic costs of river floods in Europe and the costs and benefits of adaptation

Fisher-Vanden K, Sue Wing I, Lanzi E, Popp D (2013) Modeling climate change feedbacks and adaptation responses: recent approaches and shortcomings. Clim Chang 117:481–495. https://doi.org/10.1007/s10584-012-0644-9

Gilmore EA, St.Clair T (2018) Budgeting for climate change: obstacles and opportunities at the US state level. Clim Pol 18:729–741. https://doi.org/10.1080/14693062.2017.1366891

Haasnoot M, Kwakkel JH, Walker WE, ter Maat J (2013) Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Glob Environ Chang 23:485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Hallegatte S, Hourcade J-C, Dumas P (2007) Why economic dynamics matter in assessing climate change damages: illustration on extreme events. Ecol Econ 62:330–340. https://doi.org/10.1016/j.ecolecon.2006.06.006

Hochrainer-Stigler S, Lugeri N, Radziejewski M (2014a) Up-scaling of impact dependent loss distributions: a hybrid convolution approach for flood risk in Europe. Nat Hazards 70:1437–1451. https://doi.org/10.1007/s11069-013-0885-6

Hochrainer-Stigler S, Mechler R, Pflug G, Williges K (2014b) Funding public adaptation to climate-related disasters. Estimates for a global fund. Glob Environ Chang 25:87–96. https://doi.org/10.1016/j.gloenvcha.2014.01.011

Izaurralde RC, Williams JR, McGill WB et al (2006) Simulating soil C dynamics with EPIC: model description and testing against long-term data. Ecol Model 192:362–384. https://doi.org/10.1016/j.ecolmodel.2005.07.010

Jones B, Keen M, Strand J (2013) Fiscal implications of climate change. Int Tax Public Financ 20:29–70. https://doi.org/10.1007/s10797-012-9214-3

Knutti R, Sedláček J (2013) Robustness and uncertainties in the new CMIP5 climate model projections. Nat Clim Chang 3:369–373. https://doi.org/10.1038/nclimate1716

Kolström M, Lindner M, Vilén T et al (2011) Reviewing the science and implementation of climate change adaptation measures in European forestry. Forests 2:961–982. https://doi.org/10.3390/f2040961

Kuik O, Scussolini P, Mechler R, et al (2016) Assessing the economic case for adaptation to extreme events at different scales

Kundzewicz ZW, Lugeri N, Dankers R et al (2010) Assessing river flood risk and adaptation in Europe-review of projections for the future. Mitig Adapt Strateg Glob Chang 15:641–656. https://doi.org/10.1007/s11027-010-9213-6
Leppänen S, Solanko L, Kosonen R (2015) The impact of climate change on regional government expenditures: evidence from Russia. Environ Resour Econ. https://doi.org/10.1007/s10640-015-9977-y
Lesnikowski A, Ford J, Biesbroek R et al (2015) National-level progress on adaptation. Nat Clim Chang 6:261–264. https://doi.org/10.1038/nclimate2863
Lexer MJ (2017) Interview on climate change adaptation measures in Austria's forests. Conducted during the project PACINAS
Lexer MJ, Jandl R, Nabernegg S, Bednar-Friedl B (2015) Forestry. In: Steininger KW, König M, Bednar-Friedl B et al (eds) Economic evaluation of climate change impacts. Development of a cross-sectoral framework and results for Austria. Springer International Publishing, Cham, pp 147–167
Lis EM, Nickel C (2010) The impact of extreme weather events on budget balances. Int Tax Public Financ 17: 378–399. https://doi.org/10.1007/s10797-010-9144-x
Lugeri N, Kundzewicz ZW, Genovese E et al (2010) River flood risk and adaptation in Europe-assessment of the present status. Mitig Adapt Strateg Glob Chang 15:621–639. https://doi.org/10.1007/s11027-009-9211-8
Margulis S, Narain U (2010) The costs to developing countries of adapting to climate change: new methods and estimates - the global report of the economics of adaptation to climate change study. The World Bank
McDonald J (2011) The role of law in adapting to climate change: the role of law in adapting to climate change. Wiley Interdiscip Rev Clim Chang 2:283–295. https://doi.org/10.1002/wcc.96
Mees HLP, Driessen PPJ, Runhaar HAC (2012) Exploring the scope of public and private responsibilities for climate adaptation. J Environ Policy Plan 14:305–330. https://doi.org/10.1080/1523908X.2012.707407
Melecky M, Raddatz C (2015) Fiscal responses after catastrophes and the enabling role of financial development. World Bank Econ Rev 29:129–149. https://doi.org/10.1093/wber/lht041
Mitter H, Heumesser C, Schmid E (2015a) Spatial modeling of robust crop production portfolios to assess agricultural vulnerability and adaptation to climate change. Land Use Policy 46:75–90. https://doi.org/10.1016/j.landusepol.2015.01.010
Mitter H, Schönhart M, Meyer I et al (2015b) Agriculture. In: Steininger KW, König M, Bednar-Friedl B et al (eds) Economic evaluation of climate change impacts. Development of a cross-sectoral framework and results for Austria. Springer International Publishing, Cham, pp 123–146
Moss RH, Edmonds JA, Hibbard KA et al (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747–756. https://doi.org/10.1038/nature08823
Nakićenović N, Swart R (eds) (2000) Special report on emissions scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
O'Neill BC, Kriegler E, Riahi K et al (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim Chang 122:387–400. https://doi.org/10.1007/s10584-013-0905-2
OECD (2015) The economic consequences of climate change. The economic consequences of climate change. OECD Publishing, Paris. https://doi.org/10.1787/9789264235410-en
OECD (2018a) General government revenue (indicator). Dataset. doi.org/10.1787/b68b04ae-en. Accessed 26 Nov 2018
OECD (2018b) Central government spending (indicator). Dataset. doi.org/10.1787/83a23f1b-en. Accessed 26 Nov 2018
OECD Development Assistance Committee (2016) OECD DAC Rio Markers for Climate – Handbook. https://www.oecd.org/dac/environment-development/Revised%20climate%20marker%20handbook_FINAL.pdf. Accessed 06 June 2018
Osberghaus D, Reif C (2010) Total costs and budgetary effects of adaptation to climate change: an assessment for the European Union. ZEW-Centre for European Economic Research Discussion Paper
Osberghaus D, Dannenberg A, Mennel T, Sturm B (2010) The role of the government in adaptation to climate change. Environ Plan C Gov Policy 28:834–850. https://doi.org/10.1068/c09179j
Ouattara B, Strobl E (2013) The fiscal implications of hurricane strikes in the Caribbean. Ecol Econ 85:105–115. https://doi.org/10.1016/j.ecolecon.2012.10.002
Rojas R, Feyen L, Watkiss P (2013) Climate change and river floods in the European Union: socio-economic consequences and the costs and benefits of adaptation. Glob Environ Chang 23:1737–1751. https://doi.org/10.1016/j.gloenvcha.2013.08.006
Schinko T, Mechler R, Hochrainer-Stigler S (2016) A methodological framework to operationalize climate risk management: managing sovereign climate-related extreme event risk in Austria. Mitig Adapt Strateg Glob Chang. https://doi.org/10.1007/s11027-016-9713-0
Schmid E (2004) The positive agricultural sector model Austria - PASMA. University of Agriculture and Life Sciences, Vienna

Schönhart M, Schauppenlehner T, Kuttner M et al (2016) Climate change impacts on farm production, landscape appearance, and the environment: policy scenario results from an integrated field-farm-landscape model in Austria. Agric Syst 145:39–50. https://doi.org/10.1016/j.agsy.2016.02.008

Schörghuber S, Seidl R, Rammer W, et al (2010) KlimAdapt - Ableitung von prioritären Maßnahmen zur Adaption des Energiesystems an den Klimawandel - Arbeitspaket 3: Biomasse Bereitstellung. University of Agriculture and Life Sciences, Vienna

Seidl R, Schelhaas M-J, Lindner M, Lexer MJ (2009) Modelling bark beetle disturbances in a large scale forest scenario model to assess climate change impacts and evaluate adaptive management strategies. Reg Environ Chang 9:101–119. https://doi.org/10.1007/s10113-008-0068-2

Seidl R, Schelhaas M-J, Lexer MJ (2011) Unraveling the drivers of intensifying forest disturbance regimes in Europe: drivers of forest disturbance intensification. Glob Chang Biol 17:2842–2852. https://doi.org/10.1111/j.1365-2486.2011.02452.x

Siegmeier J, Mattauch L, Franks M et al (2018) The fiscal benefits of stringent climate change mitigation: an overview. Clim Pol 18:352–367. https://doi.org/10.1080/14693062.2017.1400943

Steininger KW, König M, Bednar-Friedl B et al (eds) (2015) Economic evaluation of climate change impacts. Development of a Cross-Sectoral Framework and Results for Austria. Springer, Berlin

Steininger KW, Bednar-Friedl B, Formayer H, König M (2016) Consistent economic cross-sectoral climate change impact scenario analysis: method and application to Austria. Clim Serv 1:39–52. https://doi.org/10.1016/j.cliser.2016.02.003

Sussman F, Krishnan N, Maher K et al (2014) Climate change adaptation cost in the US: what do we know? Clim Pol 14:242–282. https://doi.org/10.1080/14693062.2013.777604

Tol RSJ (2005) Adaptation and mitigation: trade-offs in substance and methods. Environ Sci Pol 8:572–578. https://doi.org/10.1016/j.envsci.2005.06.011

Urwin K, Jordan A (2008) Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. Glob Environ Chang 18:180–191. https://doi.org/10.1016/j.gloenvcha.2007.08.002

Watkiss P, Hunt A, Blyth W, Dyszynski J (2015) The use of new economic decision support tools for adaptation assessment: a review of methods and applications, towards guidance on applicability. Clim Chang 132:401–416. https://doi.org/10.1007/s10584-014-1250-9