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Knowing the Damages is not Enough: The General Equilibrium Impacts of Climate Change

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Abstract

We show that economies may exhibit a strong endogenous macroeconomic adaptation response to climate change. If climate change induces a structural change to the more productive sector, economies can benefit from climate change though productivities in both sectors are reduced. If climate change causes structural shifts towards the less productive sector, damages are exacerbated by the intersectoral reallocation of labor and intertemporal reallocation of capital. We further assess impacts on labor movement and income distribution. We apply our analytical findings to reasonable parameters for a large set of real-world economies and find that the multiplier effect of climate change due to general equilibrium effects is sizable as it ranges between 50 and 250 percent. Thus, existing assessments of climate change impacts can be severely biased.

JEL-Codes: O410, O440, O130, O140, Q540, Q560.

Keywords: dual economy, adaptation, multi-sector growth model, general equilibrium, factor income, distribution.

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1 Introduction

This paper address the question to what extent climate change can have differentiated impacts on economic production and factor incomes in a two-sector dynamic general equilibrium setting. Integrated assessment models incorporate climate change impacts typically as change in total factor productivity (TFP). The DICE and RICE models by Nordhaus (1993, 2010), for example, formalize the impact of global warming as a multiplicative reduction of economic output which is produced by a standard neoclassical production function.

The prevalent approach of summing up the damages from bottom up studies into one aggregate damage function which is incorporated in assessment models neglects, however, macro-economic adjustment effects of climate change due to changing relative prices. There is vast evidence that economic sectors, in particular the agricultural and the industrial sector, are exposed to climate change and the resulting damages to a different extent: Analyzing global temperature shocks, Burke et al. (2015) show that agricultural value added responds stronger to heat shocks than the non-agricultural sector value added. Similarly, Dell et al. (2012) detect stronger impacts of weather shocks on the agricultural value added. An empirical analysis of export data with high sectoral resolution by Jones and Olken (2010) shows that agriculture and light manufacturing are strongly affected by temperature while the heavy industry sector shows less impact. Zivin and Neidell (2014) find that hours worked respond to high temperature – and the response is stronger in sectors that are more exposed to climate, e.g. through outdoor activities. Deryugina and Hsiang (2014) find differentiated impacts on US income on agricultural and non-agricultural activities as well.

Multi-sector models can account for these differentiated impacts of climate damages. Existing assessment models with sectorally disaggregated damages like the FUND model (Tol, 1995, 2002) disregard, however, any sectoral reallocation effects as the size of each sector is exogenous. Reallocation of economic activity from a sector strongly affected by climate change to a sector with less exposure can be understood as endogenous macro-economic adaptation which affects the overall assessment of climate impacts. Such reallocation effects are typically captured within numerical computable general equilibrium (CGE) models as, for example, in Bosello et al. (2006) and Eboli et al. (2010). Due to their complexity, these models often lack full intertemporal optimization and exhibit therefore a different investment dynamics than growth models.

The aim of this paper is to better understand sectoral as well as dynamic general equilibrium effects of climate change impacts. As numerical analyses depend on specific parametrizations and comprehensive sensitivity analyses suffer from the curse of dimensionality, we develop a stylized equilibrium model that allows to integrate crucial aspects of growth and adjustment processes. We show that dynamic general equilibrium effects of climate change can have surprising effects on economic production which cannot be found in one-sector growth models, partial equilibrium models or static general equilibrium models with incomplete intertemporal optimization. Two findings are of particular relevance: (i) Under certain conditions, climate change can have a positive impact on overall GDP and, thus, steady-state wealth although factor productivity in all sectors decreases. (ii) Total GDP can respond over-proportionally to the TFP change induced by climate change. While this multiplier effect occurs always in one-sector Ramsey growth models, the multiplier effect in two-sector models can be larger or smaller.

There are number of additional implications: Heterogeneity of the economic impacts of climate change among countries has been largely attributed to (i) spatially heterogeneous climate change (e.g. temperature and precipitation patterns) and (ii) heterogeneous exposure of the economy to climate change, e.g. due to different geographical conditions (coastal zones) or different size of affected economic sectors. We find that the discrepancy of labor productivity between the agricultural and non-agricultural sector is a crucial determinant of the magnitude and direction of the equilibrium response. Thus, countries with identical biophysical impacts and identical impacts on aggregate factor productivity can witness large variations in overall economic damages.

The developed model also allows to analyze sectoral labor movements (linked to urbanization) and distributional impacts of climate change through changes in factor incomes. So far, distributional implications have typically focused on the heterogeneous impact on *entire countries* due to differences in damage functions, economic activities or exposure to climate change (Tol et al., 2004; Mendelsohn et al., 2006). Our focus on factor incomes establishes a new channel for the distributional incidence of climate change *within countries* through structural shifts of the production.

We extend our analytical analysis with an application to real-world data to present some plausible quantitative effects of our model. We find that the multiplier effect is sizable (50 to 250 percent) and that developing countries experience large variation in the multiplier effect because of the strong divergence in sectoral labor productivity. While the general equilibrium perspective alters the assessment of GDP impacts of climate change, labor movement and distributional effects are one order of magnitude lower. The theoretical possibility that climate change will increase GDP can be ruled out for a wide range of plausible parameters.

2 The one-sector Ramsey model

To illustrate the implications of climate change on economic production with dynamic equilibrium effects, we use a standard Ramsey model with a Cobb-Douglas production function. The argument developed here is related to the numerical analysis of Fankhauser and Tol (2005) on the implications of climate damages on GDP with different approaches to model capital accumulation and growth. We focus on an analytically tractable Ramsey model (and its later extension) that provides a rich set of implications and conclusions.

Output, or GDP, is $Q^Y = \phi^Y F^Y(K, L)$ where ϕ^Y is total factor productivity (TFP), K is the capital stock, $L = 1$ the constant labor force, and $F^Y(K, L) = K^\alpha$ the Cobb-Douglas production function with $0 < \alpha < 1$ the capital income share of the economy.[1] With zero depreciation, the capital stock accumulates with investments $dK/dt = I$. In the competitive economy, factors are paid at marginal productivities. Intertemporal optimization of households with instantaneous utility function $u(C)$ with $u'(C) > 0, u''(C) < 0$ and time preference rate ρ implies $r = \rho - u''(C)/u'(C)\dot{C}$ (Euler equation). The equilibrium in the steady is fully characterized by $dK/dt = dC/dt = 0$ and $\phi^Y F^Y_K = \rho$ with $F^Y_K = \partial F^Y(\cdot)/\partial K$.

The standard approach of modeling climate change damages involves a multiplicative factor $\Omega(T)$ in the production function which depends on the change in global mean temperature T (Nordhaus, 1993; Fankhauser and Tol, 2005). $\Omega(T)$ is calibrated based on bottom-up studies that quantify the damages of climate change for different sectors and areas.[2] We therefore model climate damages as a negative relative response of TFP to the global mean temperature T, thus $d(\ln \phi^Y)/dT < 0$.[3] Calculating the total differential of the Euler equation after $\ln \phi^Y$ we obtain:

Corollary 1. *(Climate impacts) A relative change in TFP induced by climate change changes capital stocks, K, and GDP, Q^Y as follows:*

$$\frac{d(\ln K)}{dT} = \frac{1}{1-\alpha}\frac{d(\ln \phi^Y)}{dT} < \frac{d(\ln \phi^Y)}{dT} < 0 \tag{1}$$

$$\frac{d(\ln Q^Y)}{dT} = \frac{1}{1-\alpha}\frac{d(\ln \phi^Y)}{dT} < \frac{d(\ln \phi^Y)}{dT} < 0 \tag{2}$$

Proof. (i) Taking logs of the Euler equation in the steady state and inserting the Cobb-Douglas production function gives $\ln \phi^Y + \ln \alpha + (\alpha - 1)\ln K = \ln \rho$. Totally differentiating this equation after T gives after rearranging (1). (ii) Log GDP is with Cobb-Douglas technology $\ln Q^Y = \ln \phi^Y + \alpha \ln K$. Totally differentiating after T and substituting (1) for $\frac{d(\ln K)}{dT}$ gives (2). □

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[1] We abstract from population growth and exogenous technological progress in ϕ^Y for comparability with the later two-sector model where a balanced growth path exists only for very restrictive parameter constellations. In the one-sector Ramsey models, the analysis remains however valid for population and technology growth if all variables are expressed in intensive form.

[2] Nordhaus (1993) introduced and calibrated a quadratic loss function of the form $\Omega(T) = (1 + \beta T^2)^{-1}$.

[3] Modeling climate damages through changes in TFP is for Cobb-Douglas technology formally equivalent to formalizing damages as affecting resource endowments, e.g. labor force or land.

Equation 1 illustrates that a climate induced shock in TFP triggers an over-proportional change in the capital stock as $0 < \alpha < 1$ and, thus, $1/(1-\alpha) > 1$. This translates also to an over-proportional response in GDP as shown in (2). Given a particular damage function for total factor productivity $d(\ln \phi^Y)/dT$, the impact on total GDP will be greater than just the TFP impact because of the multiplier $1/(1-\alpha) > 1$. The multiplier effect is stronger in economies where α is relatively high: For $\alpha = 1/3$, the multiplier effect is already $3/2$, i.e. climate damages are 50% higher than the direct impact on TFP. While $\alpha = 1/3$ is a typical value, including human capital in the overall capital stock of the economy leads to higher aggregate capital-income share (Mankiw et al., 1992). With $\alpha = 2/3$ the multiplier effect increases damages by the factor three.

Note further that climate change has no distributional impacts in the one-sector growth model: output and capital stock change with the same elasticity and as total labor is fixed and interest rates are tied by the Euler equation, the remaining labor income changes also proportionally. Thus, earner of capital income and labor income are affected proportionally.

3 The two-sector economy

3.1 The decentralized equilibrium

We extend the one-sector economy by an additional sector. Our model set-up is inspired by dual economy models that date back to the work of Arthur Lewis (1954).[4] The aggregate sector from the one-sector Ramsey model will be called industrial sector as it uses labor L and capital K; the new sector will be called the agricultural sector as it uses a fixed factor A (land) and the remaining labor $(1-L)$ for production. The agricultural sector produces agricultural goods $Q^A = \phi^A F^A(A, (1-L))$ at technology level ϕ^A using a Cobb-Douglas production function $F^A = A^\beta (1-L)^{1-\beta}$ with β the share of the fixed-factor income within the agricultural sector. Labor migrates between both sectors such that marginal productivities are equalized and wages are $w = \phi^Y \partial F^Y(\cdot)/\partial L = p\phi^A \partial F^A(\cdot)/\partial(1-L)$. p is the relative price of agricultural goods to manufactured goods (terms of trade).

The household maximizes intertemporal utility over the aggregate consumption good $C = v(C^Y, C^A)$ given the budget constraint $w + rK + qA = C^Y + pC^A + I$ where

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[4] Eaton (1987) develops a specific-factors model of international trade with a technology structure close to ours. Drazen and Eckstein (1988) analyze an overlapping generations two sector economy where agricultural and non-agricultural goods are perfect substitutes. Hansen and Prescott (2002) consider additionally capital in the agricultural sector (assuming again perfect substitutability between agricultural and non-agricultural products). Kongsamut et al. (2001) and Ngai and Pissarides (2007) study structural change and balanced growth paths in multi-sector growth models. These models are typically concerned with dynamics of the development process and not with the shift of relative productivities due to climate change.

q is the factor price of land, I are investments into capital, C^Y is the consumption of the manufactured good and C^A consumption of the agricultural good. Optimal allocation between manufacturing and agricultural goods implies $p = \partial v(\cdot)/\partial C^A / \partial v(\cdot)/\partial C^Y$. In the two-sector economy, the decentralized equilibrium in the steady state is characterized by:

$$\phi^Y \frac{\partial F^Y(\cdot)}{\partial K} = \rho \tag{3}$$

$$p = \frac{\partial v(\cdot)/\partial C^A}{\partial v(\cdot)/\partial C^Y} \tag{4}$$

$$\phi^Y \frac{\partial F^Y(\cdot)}{\partial L} = p\phi^A \frac{\partial F^A(\cdot)}{\partial(1-L)} \tag{5}$$

$$p\phi^A \frac{\partial F^A(\cdot)}{\partial A} = q \tag{6}$$

Equation (3) is again the Euler equation, (4) describes the terms-of-trade of consumption goods and (5) the labor market and (6) the land market in the steady state. The solution of equations (3–6) for (K^*, L^*, p^*, q^*) describes the decentralized equilibrium of the economy in the steady state.

To facilitate the subsequent analysis of the equilibrium in steady state, we assume that aggregate consumption is described by a constant elasticity of substitution (CES) function:

$$v(C^Y, C^A) = \left(\lambda (C^Y)^s + (1-\lambda)(C^A)^s\right)^{1/s} \tag{7}$$

with $\lambda \in (0,1)$ denoting the preference for manufactured goods over agricultural goods and $s \in (-\infty, 1]$ the substitution parameter which is related to the elasticity of substitution between agricultural and manufactured goods σ as $s = (\sigma - 1)/\sigma$. As we have zero investments in the steady state, consumption equals production $(C^A = Q^A, C^Y = Q^Y)$ in a closed economy.

The model presented here also allows to consider the case of a small open-economy where agricultural and manufactured goods are traded at a fixed exchange rate p. In this case, the price p is external to the economy and the consumption decision can be separated from the production decision. In particular, allocations to capital, agricultural land and labor become independent from $v(C^A, C^Y)$. The production decision in the open economy is equivalent to the production decision of a closed economy where $s = 1$ and $p = (1-\lambda)/\lambda$. We will therefore in the following distinguish between a *closed economy* (with $s < 1$) and a *small open economy* (with $s = 1$) just by varying the elasticity parameter s. This allows us to flexibly consider both cases within the same model framework.

3.2 Impact on factor allocation and economic output

In what follows, we analyze how shifts in sectoral factor productivity affect factor allocation and total economic output (GDP). We define agricultural GDP as $V^A := pQ^A = p\phi^A F^A$, manufacturing GDP $V^Y := Q^Y = \phi^Y F^Y$ and total GDP, V, as the sum of the two. Sectoral labor productivity ψ is $\psi^A := V^A/(1-L)$ and $\psi^Y := V^Y/L$. Furthermore, let $\eta := V^Y/V$ be the share of the manufacturing sector's output on total output. Taking the total derivative of the steady state equilibrium (3–6) after ϕ^A and ϕ^Y and solving for marginal change in capital and labor gives:

Lemma 1. *(Factor allocation) The elasticity of the equilibrium labor and capital response to changes in productivity ϕ^A and ϕ^Y is given by:*

$$\frac{d\ln K}{d\ln \phi^A} = -\frac{s\,(1-L)}{\Gamma} \qquad \frac{d\ln K}{d\ln \phi^Y} = \frac{1}{1-\alpha} + \frac{s\,(1-L)}{\Gamma} > 0 \tag{8}$$

$$\frac{d\ln L}{d\ln \phi^A} = -\frac{s\,(1-L)}{\Gamma} \qquad \frac{d\ln L}{d\ln \phi^Y} = \frac{s\,(1-L)}{(1-\alpha)\Gamma} \tag{9}$$

with $\Gamma := s(\beta L - 1) + 1 > 0$.

Proof. See appendix. □

We see immediately that the capital stock K and labor force L in the industrial sector increases (decreases) in agricultural productivity if $s < 0 (s > 0)$. Labor allocation in the agricultural sector reacts always in the opposite direction to labor change in the non-agricultural sector. For a change in productivity in the manufacturing sector, the capital stock always increases while the sign of the change in labor allocation is equal to the sign of s.

Knowing the equilibrium response of the economy to productivity shocks, we can derive the implications for sectoral value added and total GDP:

Lemma 2. *(Output) A relative change in agricultural factor productivity ϕ^A affects sectoral and aggregate production as follows:*

$$\frac{d\ln V^Y}{d\ln \phi^A} = -\frac{s(1-L)}{\Gamma} \qquad \frac{d\ln V^Y}{d\ln \phi^Y} = \frac{1}{1-\alpha} + \frac{s(1-L)}{(1-\alpha)\Gamma} \tag{10}$$

$$\frac{d\ln V^A}{d\ln \phi^A} = \frac{sL}{\Gamma} \qquad \frac{d\ln V^A}{d\ln \phi^Y} = \frac{\Gamma - sL}{(1-\alpha)\Gamma} \tag{11}$$

$$\frac{d\ln V}{d\ln \phi^A} = -\frac{s(\eta-L)}{\Gamma} \qquad \frac{d\ln V}{d\ln \phi^Y} = \frac{1}{1-\alpha} + \frac{s(\eta-L)}{(1-\alpha)\Gamma} \tag{12}$$

Proof. See appendix. □

One can easily verify that $\eta - L > 0$ is equivalent to $\psi^Y > \psi^A$ with ψ^i the sectoral labor productivities.[5] Hence, if the labor share is lower than the production share in the industrial sector, it is over-proportionally productive. Lemma 2 shows that total GDP can even increase if agricultural productivity decreases. This is, for example, the case if the labor productivity in the industrial sector is larger than then the labor productivity in the agricultural sector and both goods are substitutes ($s > 0$).

Countries with a large discrepancy in labor productivity, i.e. where $L - \eta$ is large in absolute terms, experience a *ceterus paribus* stronger impact of agricultural productivity shifts on total GDP.

While manufacturing GDP always increases in manufacturing TFP, agricultural GDP only increases if $s < 1/(1 + (1 - \beta)L)$, thus if the substitutability is not too high. Note that in the one-sector Ramsey model, the response of GDP to a change in factor productivity is just $1/(1 - \alpha)$ (see Eq. 2). In the two-sector economy, the aggregate GDP response to a technology shock in the manufacturing sector is larger than in the one-sector economy if $sign(s(\eta - L)) > 0$. This is the case if $s > 0$ and labor productivity in manufacturing is higher than in agriculture, or if $s < 0$ and labor productivity is higher in agriculture.

We now turn to the implications of climate change for the economy. Climate change is assumed to affect sectoral productivities negatively, i.e. the relative change of productivity to a change in global mean temperature T is negative, $d(\ln \phi^i)/dT < 0$. Climate impacts can be biased, i.e. their relative size is different between the agricultural and the manufacturing sector. Let $\chi := \dfrac{d(\ln \phi^A)/dT}{d(\ln \phi^Y)/dT}$ denote the bias of damages to the agricultural sector, with $\chi > 1$ implying that damages are χ-times higher in the agricultural sector than in the industrial sector. With the previous Lemmas, we obtain

Proposition 1. *(Climate change impacts) A change in global temperature level T affects total GDP as well as labor allocation according to:*

$$\frac{d(\ln V)}{dT} = \left(\frac{1}{1-\alpha} + \frac{s(\eta - L)}{\Gamma}\left(\frac{1}{1-\alpha} - \chi\right)\right)\frac{d(\ln \phi^Y)}{dT} \tag{13}$$

$$\frac{d(\ln K)}{dT} = \left(\frac{s(1-L)}{\Gamma}(1-\chi) + \frac{1}{1-\alpha}\right)\frac{d(\ln \phi^Y)}{dT} \tag{14}$$

$$\frac{d(\ln L)}{dT} = \left(\frac{s(1-L)}{\Gamma}\left(\frac{1}{1-\alpha} - \chi\right)\right)\frac{d(\ln \phi^Y)}{dT} \tag{15}$$

Proof. (i) $\frac{d(\ln V)}{dT} = \frac{d(\ln V)}{d(\ln \phi^A)}\frac{d(\ln \phi^A)}{dT} + \frac{d(\ln V)}{d(\ln \phi^Y)}\frac{d(\ln \phi^Y)}{dT}$. Inserting $\frac{d(\ln \phi^A)}{dT} = \chi\frac{d(\ln \phi^Y)}{dT}$ and substituting (12) from Lemma 2 gives (13).

(ii-iii) The proof for (14) and (15) is analogous by using (8) and (9), respectively, from Lemma 1. □

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[5] For this, consider that $\psi^Y = V^Y/L = \eta V/L$ and $\psi^A = V^A/(1-L) = (1-\eta)V/(1-L)$.

While (13) indicates the impact of climate change on overall economic production (and, thus, welfare), (15) captures the movement of labor from the agricultural to the non-agricultural sector. The latter can also be considered as a proxy for urbanization as industrial activities take place in urban areas.

Note that we assume $\frac{d(\ln \phi^Y)}{dT} < 0$ and $\chi > 0$, i.e. a temperature increase reduces productivity in both sectors. As we have seen in (12), a lower factor productivity can actually increase total GDP due to sectoral reallocation effects. If the bias of climate damages is sufficiently strong, i.e. χ large enough, (13) can become positive and climate change actually increases total GDP.

Compare (13) again with the relative response of GDP in the one-sector Ramsey model (2), the two-sector economy can be affected stronger or not, depending on the sign of $\frac{s(\eta-L)}{\Gamma}\left(\frac{1}{1-\alpha} - \chi\right)$. The latter expression integrates the sectoral reallocation effect due to biased climate change χ which affects production differently depending on the substitution parameter s and the sectoral labor productivities, expressed in $\eta - L$. For an open economy $s > 0$ with higher labor productivity in the manufacturing sector ($\eta > L$), the multiplier effect is stronger if χ is sufficiently small; if, however, χ is sufficiently large, the entire expression can become even negative and climate change will increase overall GDP.

Equation 13 shows that the two-sector economy responds differently than the one-sector economy to climate change. In particular, diversified economies with several sectors are not *a priori* more resilient to climate change and its impact on GDP: sectoral reallocation, typically understood as a macroeconomic adaptation response, may actually exacerbate climate damages rather than reducing them.

Equation 13 further indicates that simply summing up sectoral climate damages, weighted by the value-added share of the sector, can be a highly misleading way of assessing climate damages. Actually, this naive approach would give

$$\frac{\widetilde{d(\ln V)}}{dT} = (\chi(1-\eta) + \eta)\,\frac{d(\ln \phi^Y)}{dT} \tag{16}$$

which is fundamentally different to (13).

Capital stocks (14) are stronger affected than in the one-sector model (1) if $sign(s(1-\chi)) > 0$, e.g. when agricultural goods are substitutes and damages are biased to the manufacturing sector. Regarding the effect on labor allocation (urbanization), (15) indicates that the response will be large in countries with high labor share in agriculture, $1 - L$, and when the bias χ differs strongly from the multiplier $1/(1-\alpha)$ that describes the endogenous capital response to climate change.

3.3 Distributional impacts

For assessing distributional implications, we focus on changes in the economy's aggregate factor income shares which follow directly from the sectoral factor income shares: the capital income share of the economy is $rK/V = \eta\alpha$, the labor income share of the economy is $qA/V = (1-\eta)\beta$ and labor income share is the remaining income share, i.e. $w/V = 1-\beta+\eta(\beta-\alpha)$. As α and β are fixed, distributional impacts of climate change arise if the sectoral share of the economy η is affected: A higher manufacturing sector increases the capital income and reduces land income, and wage income increases only if $\beta > \alpha$ which is equivalent to $\psi^A > \psi^Y$ as well as to $L > \eta$.[6] Table 1 illustrates the distributional implications for all possible parameter constellations.

	Capital income	Land income	Labor income	
			$\psi^Y > \psi^A$	$\psi^Y < \psi^A$
$d\eta > 0$	+	−	−	+
$d\eta < 0$	−	+	+	−

Table 1: Impact of sectoral shifts on aggregate factor income shares. η is the share of value added of the manufacturing sector on total GDP.

Hence, understanding the distributional impacts of climate change requires to analyze how η responds to changes in sectoral factor productivites.

Lemma 3. *(Sectoral shift) A marginal change in agricultural factor productivity ϕ^A affects sectoral and aggregate production as follows:*

$$\frac{d\eta}{d\ln(\phi^A)} = -\eta s\frac{1-\eta}{\Gamma} \qquad\qquad \frac{d\eta}{d\ln(\phi^Y)} = \eta s\frac{1-\eta}{(1-\alpha)\Gamma} \tag{17}$$

Proof. $\eta = V^Y/V$. With the chain rule, we have $\frac{d\eta}{d\ln(\phi^i)} = \left(\frac{dV^Y}{d\ln(\phi^i)} - \eta\frac{dV}{d\ln(\phi^i)}\right)\frac{1}{V}$. Substituting (10–12), we obtain the result after re-arranging. □

The sign of the sectoral shift depends only on the sign of s. If climate change affects only the manufacturing sector, the relative size of the manufacturing sector decreases if $s > 0$ and increases if $s < 0$; the labor income share would therefore increase for $s > 0$ and decrease for $s < 0$, assuming that labor productivity is higher in the manufacturing sector. Climate change affecting the agricultural sector only shows the opposite dynamics. The combined effect of climate change on labor income share is expressed in

Proposition 2. *(Labor income share) Climate change affects the labor income share*

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[6] The first equivalence follows from labor market equilibrium (5); the second was discussed above.

w/V as follows

$$\frac{d(w/V)}{dT} = (\beta - \alpha)\left[\frac{1}{1-\alpha} - \chi\right]\eta s \frac{1-\eta}{\Gamma}\frac{d(\ln\phi^Y)}{dT} \tag{18}$$

Proof. $\frac{d\eta}{dT} = \left(\chi\frac{d\eta}{d(\ln\phi^A)} + \frac{d\eta}{d(\ln\phi^Y)}\right)\frac{d(\ln\phi^Y)}{dT}$ which, using (17) simplifies to $(\chi(\alpha-1)+1)\frac{d\eta}{d(\ln\phi^Y)}\frac{d(\ln\phi^Y)}{dT}$. As $\frac{d(w/V)}{dT} = (\beta-\alpha)\frac{d\eta}{dT}$ (see beginning of this section), the result follows with substituting (17). □

Comparing (18) with (13), the labor income share tends to be in opposite direction than the intersectoral multiplier effect. Thus, when the multiplier effect is very strong, labor income is affected less than proportional.

4 Numerical application

In order to obtain a quantitative estimation of the implications of climate change for economies, we apply the analytical findings to realistic parameter settings. Due to large existing uncertainties, we leave the specification of a (sectoral) damage function $\frac{d(\ln\phi^Y)}{dT}$ aside and normalize our results relative to any given (naive) damage function as expressed in (16).

4.1 Parameters and data

We consider two scenarios for the elasticity of substitution: $\sigma = 2$ refers to an open economy where climate change affects sectoral factor productivities of the individual country, ignoring changes in factor productivity in other countries. This setting is in particular relevant if climate change impacts (e.g. changed precipitation patterns) and damage functions are very heterogeneous among countries. The value for σ is typical for Armington elasticities used in equilibrium trade models that capture imperfect substitutability between domestic and foreign products (see, e.g. the GTAP database (Aguiar et al., 2012, Ch. 14)). The second case of low substitutability, $\sigma = 0.5$, is relevant for closed economies where food and non-food products are complements in consumer utility. It applies also to an open economy when climate change impacts are very homogeneous among countries and all countries of the global economy (which is a closed economy) experience similar shifts in sectoral productivities.

Due to large uncertainties in the assessment of climate impacts, we consider three values for the bias of damages to the agricultural sector: $\chi = 0.5, 1, 2$. Dell et al. (2012, Table 5) find that a 1K temperature shock in poor countries provokes 30 to 76 percent higher impacts on the agricultural value added compared to the industrial value added. Precipitation shocks are, however, ambiguous (and neither consistent across specifications, nor statistically significant). Burke et al. (2015) also estimate a steeper (non-linear) damage function for the agricultural sector than for the industrial sector in developing countries. These findings are not directly transferable to our model framework as these works investigate historical *weather shocks*, not future *climate change* which takes place gradually and implies additional damages, e.g. through sea-level rise. The latter, for example, affects a larger share of urban areas than of agricultural land (Dasgupta et al., 2009). As additionally urban areas are several times more productive than agricultural areas, sea-level rise may hit the non-agricultural sector relatively more than the agricultural sector. Hence, it remains unclear whether climate damages will be stronger biased to the agricultural or to the non-agricultural sector.

The share of the non-agricultural sector η and the share of the population working in the non-agricultural sector L are obtained from the World Development Indicators (most recent value). These values are available for 186 countries. α and β in the production function are calculated using factor income shares from several Social Accounting Matrices (SAMs) (see Appendix). As the latter data is available only for small set of developing countries, we employ an average value of $\alpha = 0.56$ and $\beta = 0.31$ for all countries in our simulations.

4.2 Damage multiplier

We first analyze how strong the intertemporal and sectoral equilibrium response changes the aggregate GDP according to (13) compared to a standard damage function approach where sectoral damages are summed up, i.e. where $d(\ln V)/dT = (\chi(1-\eta) + \eta)d(\ln \phi^Y)/dT$. We denote the ratio of these two expressions as *damage multiplier* as it indicates by how much the usual (static) damage function is altered if general equilibrium effects are considered. A multiplier greater than one implies that damages are higher if general equilibrium effects are considered.

Fig. 1 shows the numerical results for the case of complements and substitutes. Three observations follow immediately: (i) the multiplier effect is sizable, increasing climate damages by a factor of three or more, (ii) poor countries experience much higher dispersion of the multiplier for different parameter constellations, and (iii) for wealthier countries, the multiplier converges to the multiplier of the one-sector growth model (see Eq. 2) which is just $1/(1-\alpha) = 2.27$. The last two findings are directly related to the fact that labor and value added share are very small and very similar for wealthier countries. As a consequence, $\eta - L \approx 0$ (see Fig. 3 in the Appendix) and only the intertemporal multiplier effect from the one-sector Ramsey model remains which is independent from damage bias and substitutability (see again Eq. 13).

Our numerical results show that there is not a single country where the multiplier is less then one, i.e. where macroeconomic adaptation reduces output to less than

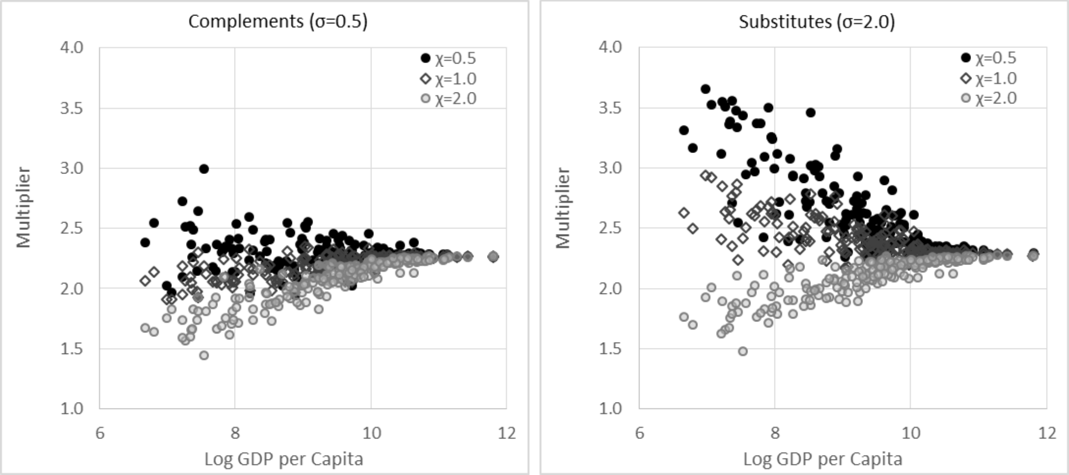

Figure 1: Damage multiplier for closed ($\sigma = 0.5$) and open ($\sigma = 2.0$) economies and different degrees of agricultural damage bias (χ). GDP is in PPP in constant 2011 international US$ per capita.

aggregate factor productivity. In particular, obtaining a negative multiplier which would imply aggregate benefits of climate change seems to be unlikely. This becomes also apparent if we calculate the critical bias $\tilde{\chi}$ needed to reverse the sign in (13), which is $\tilde{\chi} = \frac{1}{1-\alpha} + \frac{\Gamma}{s(\eta-L)(1-\alpha)}$. Calculating $\tilde{\chi}$ for our country sample yields that $\tilde{\chi} < 0$ in case of complements for all countries where $\eta > L$ (which is the vast majority). Hence, climate change would need to increase agricultural productivity while simultaneously decreasing manufacturing productivity in order to have a positive impact on aggregate GDP.[7] In case of substitutes, positive aggregate impacts of climate change due to structural shift from agriculture to manufacturing are neither likely as the bias needs to be unrealistically high: There are only very few countries with $\tilde{\chi} < 10$ and the lowest $\tilde{\chi}$ is 6.8 (see Tab. 3 in the Appendix).

4.3 Sectoral labor migration

Labor movements from the agricultural to the industrial sector can be associated to higher urbanization rates. Applying (15) to our parameter set and normalizing again by the naive damage function without equilibrium effects shows the magnitude of labor movements as a response of a marginal reduction in aggregate productivity. The upper panel of Fig. 2 indicates that the labor market effects are rather small. As a direct consequence from (15), the labor market is hardly affected for $\chi = 2 \approx 1/(1-\alpha)$. Poor countries show again higher variability in impacts as $L(1-L)$ is larger for poor economies (see Fig. 3 in the Appendix).[8] In the case of substitutes, higher urbanization

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[7] The highest $\tilde{\chi}$ is -5.7 while the average $\tilde{\chi}$ is -248.7, implying unrealistic high biases for almost all countries.

[8] Additionally, $1/\Gamma$ is large for poor countries in case of substitutes.

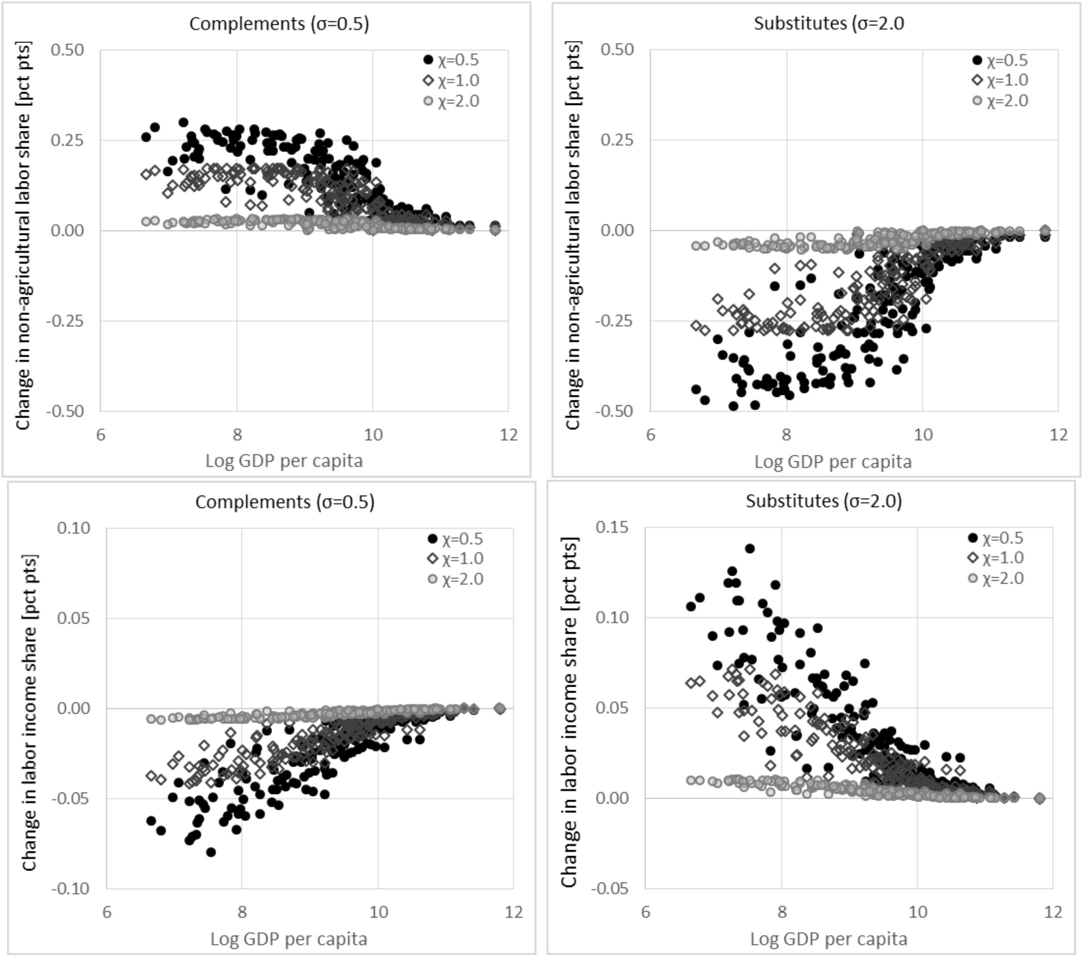

Figure 2: Implication of 1% aggregate productivity reduction due to climate damage for labor markets (upper panel) and labor income share (lower panel) in closed ($\sigma = 0.5$) and open ($\sigma = 2.0$) economies for different degrees of agricultural damage bias (χ). GDP is in PPP in constant 2011 international US$ per capita.

can only be expected for a very large bias of damages ($\chi > 2.27$). For the case of complements, urbanization will increase if damages are biased to the industrial sector ($\chi = 0.5$). The magnitudes are, however, moderate: For a 10% aggregate productivity shock, hardly more than 2.5% of the entire labor force will shift to the manufacturing sector.

4.4 Labor income shares

Additionally to the overall reduction of output which reduces also wages, climate change affects the relative share of output paid as labor income. Applying (18) to the data, we calculate the impact of climate change on the labor income share as a key indicator for distributional implications. A lower labor income share tends to increase inequality as wealthier households typically receive relatively higher incomes from capital. The lower panel of Fig. 2 shows again that income shares are hardly affected for $\chi = 2$, which is again due to $\chi \approx 1/(1-\alpha)$. If climate damages are biased to the industrial sector, workers gain (relatively) in case of substitutes and loose (relatively) in case of complements. The magnitudes are again moderate: In case of complements, a ten percent aggregate productivity shock would reduce labor income share by less than 0.8 percentage points. Compared to the overall reduction in output by more than ten percent (considering the multiplier), the distributional effect is rather small.

5 Conclusions

Assessing the impacts of climate change has been always been attended by controversial debates. The Stern (2007) Review triggered a discussion on the role of normative parameters to assess the damages of climate change (Nordhaus, 2007; Dasgupta, 2008; Stern, 2008). Also, controversies exist on the functional form, parametrization and theoretical foundation of the damage function that relates GDP to temperature levels (Pindyck, 2013) and how uncertainties on structural parameters can affect the overall assessment of climate impacts substantially (Weitzman, 2011). This paper adds another dimension of uncertainty for climate impact assessments: The endogenous equilibrium response, or macro-economic adaptation, of economies to changing factor productivities.

Our stylized two-sector growth model indicates that economies may show a strong endogenous macroeconomic adaptation response to climate change. This response is driven by intertemporal as well as intersectoral equilibrium effects and exacerbates or reduces the original productivity shock induced by climate change. If climate change impacts are sufficiently biased to the sector with the lower labor productivity, steady state wealth can even increase although factor productivities in both sectors are reduced. This finding occurs if climate change induces a structural change involving labor reallocation to the more productive sector.

Our analysis adds a new form of heterogeneity of climate impacts among countries. Previous research identified different local climate dynamics or different sector composition. Accordingly, climate damages were considered to be large for developing countries as they have a large agricultural sector which depends stronger on climate conditions than the manufacturing sector. Our model shows that the impact of sectoral general equilibrium effects is large in economies where labor productivities differ strongly between sectors. McMillan et al. (2014) find that developing countries experience high divergence in sectoral labor productivities while labor productivities in industrialized countries show lower variance among sectors. Thus, independent from the relative size of the agricultural sector and local climate change dynamics, developing countries may be stronger affected by climate change than industrialized countries as the sectoral general equilibrium effects are particularly strong.

The intertemporal adjustment to climate change operates through savings and generally exacerbates the productivity shock the higher the capital income share of the economy is. This multiplier effect is of particular relevance if human capital accumulation is considered to be an important form of capital, as this raises the capital income share of the economy and, thus, increases the multiplier effect considerably.

Additional to aggregate economic impacts, our model allows to assess potential impacts of climate change on labor movement (driving urbanization) and income distribution. Contrary to one-sector growth models, climate change can increase or decrease labor income shares, depending on the bias of damages to the sector with higher labor productivity and the substitutability between agricultural and non-agricultural goods.

We apply our analytical findings to reasonable parameters for a large set of real-world economies and find that the multiplier effect is sizable as it ranges between 50 and 250 percent. Thus, existing assessments of climate change impacts can be severely biased. Developing countries experience large variation in the multiplier effect because of the strong divergence in sectoral labor productivity. The theoretical possibility that reductions in aggregate productivity will increase GDP can be ruled out for a wide range of plausible parameters. Contrary to GDP, labor movement and distributional effects are much lower even for high climate impacts. Our analysis brings a new perspective on climate-economy models, as equilibrium effects may even dominate the biophysical or first-order economic impacts of climate change.

The model presented here can be extended to account for exogenous technological change and population growth by using the intense form, i.e. by normalizing variables by effective worker. An important condition for balanced growth is, however, that land productivity grows at a rate that depends on labor productivity and population growth. Further model extensions to consider are the inclusion of non-homothetic preferences which allows to study sectoral impacts of climate change from a demand side (Kongsamut et al., 2001). One of the most important implications for research on climate change is, however, to extend dynamic one-sector or static multi-sector integrated assessment models by intersectoral and intertemporal equilibrium conditions. Otherwise, the quantitative assessment of the economic impacts of climate change might be seriously biased.

A Proofs

A.1 Proof of Lemma 1

With the Cobb-Douglas production function, (5) becomes

$$p = \frac{1-\alpha}{1-\beta}\frac{1-L}{L}\frac{Q^Y}{Q^A} \tag{19}$$

As v is a homothetic function, price is a function of the ratio of the quantities consumed, i.e. we can express (4) as

$$p = f\left(\frac{Q^A}{Q^Y}\right) \tag{20}$$

with $f'(\cdot) < 0$. Combining (19) and (20) gives

$$\frac{Q^A}{Q^Y} f\left(\frac{Q^A}{Q^Y}\right) = \frac{1-\alpha}{1-\beta}\frac{1-L}{L} \tag{21}$$

and taking logs yields

$$\ln Q^A - \ln Q^Y + \ln\left[f\left(\frac{Q^A}{Q^Y}\right)\right] = \ln(1-\alpha) - \ln(1-\beta) + \ln(1-L) - \ln L \tag{22}$$

Next, we totally differentiate the terms in (22) after $\ln\phi^i$ with $i \in \{A, Y\}$. Because of constant elasticity of substitution σ, we have further $\frac{f'(Q^A/Q^Y)Q^A}{f(Q^A/Q^Y)Q^Y} = -1/\sigma = s - 1$. Thus,

$$\begin{aligned}
\frac{d\ln\left[f\left(\frac{Q^A}{Q^Y}\right)\right]}{d(\ln\phi^i)} &= \frac{f'(Q^A/Q^Y)}{f(Q^A/Q^Y)}\frac{d(Q^A/Q^Y)}{d(\ln\phi^i)} \\
&= (s-1)\frac{Q^A}{Q^Y}\frac{d(Q^A/Q^Y)}{d(\ln\phi^i)} = (s-1)\frac{d\ln(Q^A/Q^Y)}{d(\ln\phi^i)} \\
&= (s-1)\left(\frac{d(\ln Q^A)}{d(\ln\phi^i)} - \frac{d(\ln Q^Y)}{d(\ln\phi^i)}\right) \qquad (23)
\end{aligned}$$

With this, the total derivative of (22) after $\ln\phi^i$ becomes

$$\begin{aligned}
s\left(\frac{d(\ln Q^A)}{d(\ln\phi^i)} - \frac{d(\ln Q^Y)}{d(\ln\phi^i)}\right) &= \frac{d(\ln(1-L))}{d(\ln\phi^i)} - \frac{d(\ln L)}{d(\ln\phi^i)} \\
&= -\frac{d(\ln L)}{d(\ln\phi^i)}\frac{L}{1-L} - \frac{d(\ln L)}{d(\ln\phi^i)} \\
&= -\frac{1}{1-L}\frac{d(\ln L)}{d(\ln\phi^i)} \qquad (24)
\end{aligned}$$

Using the Cobb-Douglas function, we obtain further

$$\frac{d(\ln Q^A)}{d(\ln \phi^i)} = \frac{d(\ln \phi^A)}{d(\ln \phi^i)} - \frac{(1-\beta)L}{1-L}\frac{d(\ln L)}{d(\ln \phi^i)} \tag{25}$$

$$\frac{d(\ln Q^Y)}{d(\ln \phi^i)} = \frac{d(\ln \phi^Y)}{d(\ln \phi^i)} + \alpha\frac{d(\ln K)}{d(\ln \phi^i)} + (1-\alpha)\frac{d(\ln L)}{d(\ln \phi^i)} \tag{26}$$

Taking logs of (3) gives $\ln \rho = \ln \phi^Y + \ln \alpha + (\alpha - 1)\ln K + (1-\alpha)\ln L$. Totally differentiating this after $\ln \phi^i$ and solving for $d(\ln K)/d(\ln \phi^i)$ yields

$$\frac{d(\ln K)}{d(\ln \phi^i)} = \frac{1}{1-\alpha}\frac{d(\ln \phi^Y)}{d(\ln \phi^i)} + \frac{d(\ln L)}{d(\ln \phi^i)} \tag{27}$$

Substituting (27) into (26) and this, in turn, together with (25) into (24), we can solve for $\frac{d(\ln L)}{d(\ln \phi^i)}$ which gives (9). Note that $\frac{d(\ln \phi^Y)}{d(\ln \phi^i)} = 0$ for $i = A$ and $\frac{d(\ln \phi^Y)}{d(\ln \phi^i)} = 1$ for $i = Y$. Substituting (9) into (27) gives finally (8).

A.2 Proof of Lemma 2

(i) Inserting $\ln V^Y = \ln Q^Y = \ln \phi^Y + \alpha \ln K + (1-\alpha)\ln L$ into $\frac{d \ln V^Y}{d \ln \phi^A}$ and into $\frac{d \ln V^Y}{d \ln \phi^Y}$ and substituting (8–9) gives (10).

(ii) With (20) and the Cobb-Douglas function,

$$\ln V^A = \ln p + \ln Q^A = \ln f(Q^A/Q^Y) + \ln Q^A \tag{28}$$

Taking the total derivative after productivity of the price $p = f(\cdot)$ first, we can use (23), and the derivative of (28) becomes

$$\frac{d(\ln V^A)}{d(\ln \phi^i)} = s\frac{d(\ln Q^A)}{d(\ln \phi^i)} + (1-s)\frac{d(\ln Q^Y)}{d(\ln \phi^i)} \tag{29}$$

With $\ln Q^A = \ln \phi^A + \beta \ln A + (1-\beta)\ln(1-L)$, we have

$$\frac{d(\ln Q^A)}{d(\ln \phi^A)} = 1 - \frac{(1-\beta)L}{1-L}\frac{d(\ln L)}{d(\ln \phi^A)} \tag{30}$$

$$\frac{d(\ln Q^A)}{d(\ln \phi^Y)} = -\frac{(1-\beta)L}{1-L}\frac{d(\ln L)}{d(\ln \phi^Y)} \tag{31}$$

Substituting (8–9) into (30–31) and this, together with the finding from (i), into (29) gives (11), which is the final result.

(iii)

$$\frac{d(\ln V)}{d(\ln \phi^i)} = \frac{1}{V}\frac{dV}{d(\ln \phi^i)} = \frac{1}{V}\left(\frac{dV^A}{d(\ln \phi^i)} + \frac{dV^Y}{d(\ln \phi^i)}\right) \tag{32}$$

$$= \frac{1}{V}\left(V^A \frac{d(\ln V^A)}{d(\ln \phi^i)} + V^Y \frac{d(\ln V^Y)}{d(\ln \phi^i)}\right) \tag{33}$$

$$= (1-\eta)\frac{d(\ln V^A)}{d(\ln \phi^i)} + \eta \frac{d(\ln V^Y)}{d(\ln \phi^i)} \tag{34}$$

Inserting the results from part (i) and (ii) (i.e. Eqs. 10–11) into (34) gives the result (12).

B Factor income shares

Country	Base year	capital income	land income	η	α	β	Source for SAM
Bangladesh	1993/94	0.435	0.129	0.741	0.59	0.50	Fontana and Wobst (2001)
Brazil	1995	0.514	0.033	0.942	0.55	0.57	Cattaneo (2002)
China	2007	0.453	0.020	0.892	0.51	0.19	Zhang and Diao (2013)
El Salvador	2000	0.649	0.015	0.895	0.73	0.14	Acevedo (2004)
Ghana	2005	0.238	0.076	0.591	0.40	0.19	Breisinger et al. (2007)
Indonesia	1995	0.424	0.062	0.829	0.51	0.36	Bautista et al. (1999)
Kenya	2003	0.511	0.048	0.710	0.72	0.17	Kiringai et al. (2006)
Malawi	1998	0.336	0.108	0.644	0.52	0.30	Chulu and Wobst (2001)
Mexico	2008	0.652	0.014	0.967	0.67	0.42	Debowicz and Golan (2012)
Nigeria	2006	0.433	0.110	0.680	0.64	0.34	Nwafor et al. (2010)
Peru	2002	0.507	0.043	0.917	0.55	0.52	Nin-Pratt et al. (2011)
Tanzania	2001	0.397	0.041	0.671	0.59	0.12	Thurlow and Wobst (2003)
Uganda	1999	0.237	0.226	0.615	0.38	0.59	Dorosh et al. (2002)
Vietnam	1997	0.282	0.093	0.742	0.38	0.36	Nielsen (2002)
Zambia	2001	0.528	0.012	0.780	0.68	0.05	Thurlow et al. (2008)
Zimbabwe	1991	0.488	0.023	0.847	0.58	0.15	Thomas and Bautista (1999)
Mean		0.443	0.066	0.779	0.56	0.31	
Median		0.444	0.046	0.761	0.56	0.32	

Table 2: Factor income shares and derived α and β from various social accounting matrices. The share of the non-agricultural sector on total GDP, η, is obtained from the World Development Indicators. $\alpha = \tilde{\alpha}/\eta$ and $\beta = \tilde{\beta}/(1-\eta)$ with $\tilde{\alpha}$ and $\tilde{\beta}$ the capital and land income share of the entire economy.

C Additional figures and tables

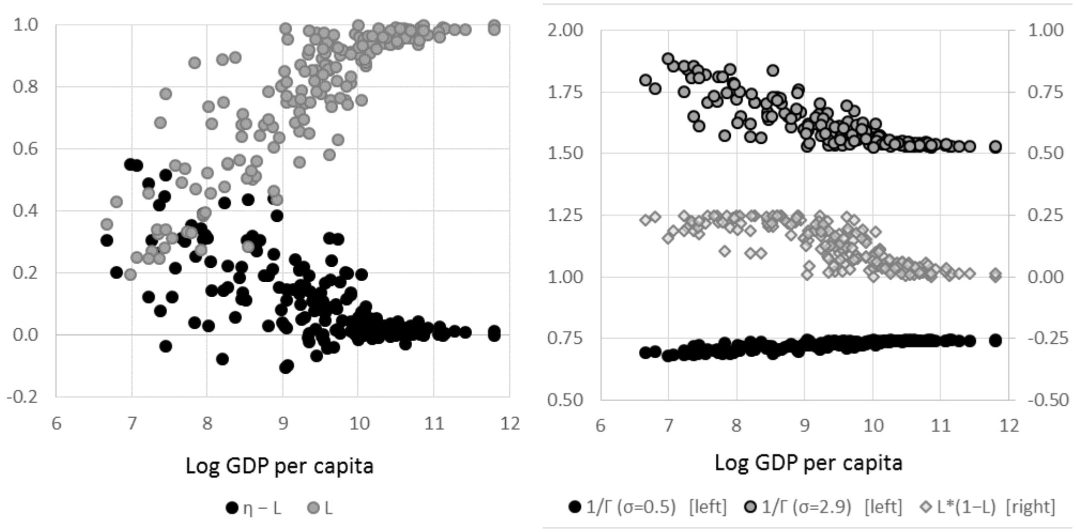

Figure 3: Model parameters and related expressions for countries.

ISO3	GDP/cap	L	η	χ_{crit}
BTN	7,456	0.44	0.82	9.0
BFA	1,545	0.33	0.66	9.8
CMR	2,836	0.39	0.78	8.8
GEO	7,233	0.47	0.91	8.2
GIN	1,165	0.25	0.80	6.8
LAO	5,076	0.29	0.72	7.9
MDG	1,373	0.25	0.74	7.3
MOZ	1,077	0.20	0.75	6.6
NPL	2,265	0.34	0.66	9.9
PNG	2,724	0.28	0.62	9.4
RWA	1,584	0.25	0.67	8.1
TZA	2,421	0.33	0.69	9.3
UGA	1,689	0.28	0.73	7.8
ZMB	3,725	0.48	0.90	8.4
ZWE	1,709	0.34	0.86	7.1

Table 3: Damage bias $\chi > \chi_{crit}$ necessary to reverse the negative impacts of climate change in the case of substitutes ($s > 0$). Only countries with $\chi_{crit} \leq 10$ and positive χ are shown. GDP is in PPP in constant 2011 international US$ per capita.

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