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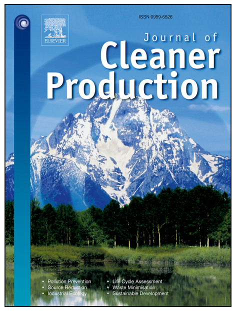

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Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies

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Abstract

Achieving sustainable development requires the decoupling of natural resource use and environmental pressures from economic growth and improvements in living standards. G7 leaders and others have called for improved resource efficiency, along with inclusive economic growth and deep cuts in global greenhouse emissions. However, the outlooks for and interactions between global natural resource use, resource efficiency, economic growth and greenhouse emissions are not well understood. We use a novel multi-regional modeling framework to develop projections to 2050 under existing trends and three policy scenarios. We find that resource efficiency could provide pro-growth pro-environment policies with global benefits of USD $2.4 trillion in 2050, and ease the politics of shifting towards sustainability. Under existing trends, resource extraction is projected to increase 119% from 2015 to 2050, from 84 to 184 billion tonnes per annum, while greenhouse gas emissions increase 41%, both driven by the value of global economic activity more than doubling. Resource efficiency and greenhouse abatement slow the growth of global resource extraction, so that in 2050 it is up to 28% lower than in existing trends. Resource efficiency reduces greenhouse gas emissions by 15–20% in 2050, with global emissions falling to 63% *below* 2015 levels when combined with a 2°C emissions pathway. In contrast to greenhouse abatement, resource efficiency boosts near-term economic growth. These economic gains more than offset the near-term costs of shifting to a 2°C emissions pathway, resulting in emissions in 2050 well below current levels, slower growth in resource extractions, and faster economic growth.

1. Introduction

Sustainable development requires natural resource use and environmental pressures to be decoupled from economic growth and improvements in living standards (UNEP 2011), to prevent pressures and impacts exceeding planetary boundaries (Steffen et al. 2015). G7 leaders (Leaders 2015) and the United Nations Sustainable Development Goals (UN 2015) highlight the potential for improved resource efficiency to achieve this decoupling. However, the potential physical and economic implications of resource efficiency are not well understood at the global scale, with most studies focused on specific sectors (Mercure et al. 2014), or on high-income countries (Pollitt and Chewpreecha 2009; Ekins et al. 2011).

In our research we investigate the potential for economically attractive resource efficiency and assess co-benefits between resource efficiency and greenhouse gas abatement. There are ample examples of modeling the economic effects of climate mitigation using models with extensive economic sector detail (Lutz and Meyer 2009; Pollitt et al. 2015). There is, however, a knowledge gap with regard to scenarios for material use and resource efficiency and for linkages between natural resources and climate. We address this research gap and ask to which extent global resource use may be reduced by well-designed policies. We also ask about the mix of economic and environmental benefits that may be achieved and consider which policies and approaches would best achieve the desired outcome of decoupling of economic growth and human well-being from natural resource use and greenhouse gas emissions.

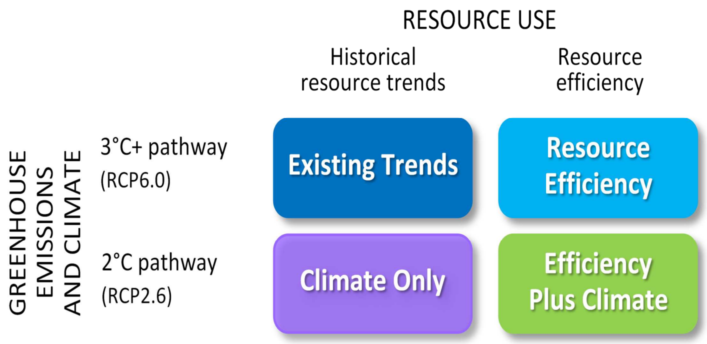
Resource efficiency, in our research, refers to the economic efficiency of the use of materials – biomass, fossil fuels, metal ores and non-metallic minerals – and can be expressed either as material productivity (GDP per unit of material use) or material intensity (material use per unit of GDP). The two are inverse. In doing so we describe efficiency at the level of the macro economy.

We use a novel global multi-model framework to develop natural resource use projections to 2050 under *Existing Trends* and three policy scenarios, with dynamic demand, supply and incentive effects. It projects the volume of all material flows, divided into ten subcategories, along with energy (by source and end use), and greenhouse gases (see Table 2.). The primary model is the Global Trade and Environmental Model (GTEM), an economy-wide computable general equilibrium (CGE) model with 28 regions and 21 industry sectors (see Table 1. and Table SI.2). GTEM has an established track record in climate policy (Garnaut 2007, 2011) and recent extensions to further account for climate impacts (Scealy et al. 2012; Cai et al. 2016; Cai et al. 2015). We link GTEM to GLOBIOM (Havlík et al. 2011; Havlík et al. 2014) to provide additional detail on land use, agricultural production, and biomass supply. Technical potential for improving resource efficiency is based on available literature, and the IRP report to the G7 (UNEP 2016). More information is provided under *Methods* below.

There are other models that provide a good representation of intra-economic relationships and trade relations, such as for example the GINFORS model (Lutz and Giljum 2009; Giljum et al. 2008) at the Institute of Economic Structures Research which combines econometric analysis with input-output analysis embedded in a complete macroeconomic framework. Cambridge Econometrics runs E3ME (Pollitt et al. 2015), a global econometric model focusing on economy, energy and natural resources. The Threshold 21 model of the Millennium Institute (Bassi and Shilling 2010) is a systems dynamic representation of economy-environment interrelationships designed to assess policy alternatives in development planning. In contrast to these integrated models we have chosen a multi-model framework with a general equilibrium model at its core linked to sectoral technology models that present realistic scenarios of technological change. We test the economic implications of technology choice under different policy scenarios using a standard economic model.

We undertake a simple scenario analysis which contrasts a baseline scenario (existing trends) with resource efficiency and greenhouse abatement policy scenarios. We then combine resource efficiency and greenhouse abatement policies in a fourth scenario (efficiency plus). Each of the four scenarios represents a specific combination of potential future resource use trends and future greenhouse gas emissions pathways (as shown in Figure 1).

Figure 1 Scenarios for resource efficiency and greenhouse abatement



Existing Trends (H3) is calibrated to historical natural resource use trends (H) and greenhouse policies that would see a 3°C increase (3) in temperatures by the end of the century, rising to around 4°C after that. Natural resource use trends are applied across major world regions, accounting for changes in GDP per capita. *Existing Trends* is aligned with the "middle of the road" social-economic pathway SSP2 (O'Neill et al. 2015; IIASA 2015) and greenhouse emissions match the trajectory for RCP6.0 (Rogelj et al. 2012), a little lower than most interpretations of the Paris pledges (INDCs) to 2030.

Resource Efficiency (E3) assumes a package of stylized measures that drive improvements in resource efficiency (E) from 2020 (described in methods below), with the same greenhouse policies (3) as *Existing Trends*.

Ambitious Climate (H2) assumes the same natural resource use policies (H) as *Existing Trends*, but that the world adopts ambitious greenhouse gas abatement policies (detailed in SI-4) capable of limiting likely global temperature increases to 2°C (2) above pre-industrial levels. This goes beyond the specific pledges made in Paris for 2025–2030, with global greenhouse emissions to 2050 calibrated to match RCP2.6.

Efficiency Plus (E2) combines the resource efficiency settings (E) and greenhouse gas abatement settings (2) to explore potential policy interactions. We find this scenario has a higher chance of limiting climate change to 2°C than any other scenario.

The research we present here extends our previous decoupling analysis (Schandl et al. 2015) by integrating the material flows in the CGE model and enabling a thorough assessment of the rebound effect that results from resource efficiency improvements.

2. Methods

2.1 Global regions and groups

The version of GTEM used has 28 regions, including 17 individual nations, and 11 continental aggregations of nations (grouped by latitude where possible to facilitate climate impact assessments). We group the 28 regions into current geopolitical constituencies, future income categories, and physical trade balances: see Table 1.. Future income categories are based on projected GDP per capita in 2050 in real USD 2015 under *Efficiency Plus*: high spans $50,000-$90,000; medium spans $13,500-$30,000 and includes BRICS except India plus Mexico and Central Europe; while low spans $1,500-$12,750 and includes ROW and India. At the boundary between medium and low income, the GDP per capita of Southern South America (low) is 7% lower than South Africa (medium) under *Efficiency Plus* but 7% higher under *Existing Trends*.

We provide an overview of the world in 2050 under *Existing Trends* and *Efficiency Plus* in the Supplementary Information, including the global distribution of population, GDP per capita, resource use (DMC) and productivity, energy supply and greenhouse gas emissions.

Table 1. GTEM countries, regions and groups.

Region	Code	Current Group	Future Income	PTB (a)
Asia-Pacific				
Australia	**AUS**	Other OCED	High	Exporter
China	**CHN**	BRICS	Medium	Importer
East Asia and Oceania	**EAO**	ROW	Low	Exporter
India	**IND**	BRICS	Low	Importer
Indonesia	**IDN**	ROW	Low	Exporter
Japan	**JPN**	Other OCED	High	Importer
Korea	**KOR**	Other OCED	High	Importer
New Zealand	**NZL**	Other OCED	High	Exporter
South Asia	**SAS**	ROW	Low	Exporter
North America				
Canada	**CAN**	Other OCED	High	Exporter
Mexico	**MEX**	Other OCED	Medium	
United States	**USA**	G7	High	Importer
South and Central America				
Brazil	**BRA**	BRICS	Medium	Exporter
Central America	**CAM**	ROW	Low	Importer
Northern South America	**NSA**	ROW	Low	Exporter
Southern South America	**SSA**	ROW	Low	Exporter
Europe				
Central Europe	**CEU**	ROW	Medium	Importer
France	**FRA**	G7	High	Importer
Germany	**DEU**	G7	High	Importer
Italy	**ITA**	G7	High	Importer
United Kingdom	**GBR**	G7	High	Importer
Western Europe (ex-G7)	**WEU**	Other OCED	High	Importer
West Asia				
East Europe and West Asia	**EEW**	ROW	Low	Exporter
Russia	**RUS**	BRICS	Medium	Exporter
Africa				
Central Africa	**CAF**	ROW	Low	Importer
North and West Africa	**NWA**	ROW	Low	Exporter
Other Africa	**OAF**	ROW	Low	Exporter
South Africa	**SAF**	BRICS	Medium	Exporter

Notes: (a) PTB = Physical Trade Balance in natural resources. See Table S# for mapping of specific countries to regions.

2.2 Material flows, energy and greenhouse emissions accounts

The analysis demonstrates a novel whole-of-economy approach to projecting natural resource extraction (DE), trade (PTB), and use (DMC). We use a standard CGE model to provide physical volume indexes for ten subcategories of material flows, based on the input-output structure of the model, as shown in Table 2. . These are applied to base-year data from the UNEP International Resource Panel (UNEP 2016) to generate projections to 2050, accounting for economic dynamics, resource use along national and international supply chains, and related energy use and greenhouse emissions. Material flow indicators follow the methodological guidelines provided by the European Statistical Office (EUROSTAT 2013) and the OECD, and are consistent with the international standards for national and global material flow accounting (Fischer-Kowalski et al. 2011). This production-oriented approach can be extended through input-output analysis to provide consumption-based material footprints by region (Schandl et al. 2015), but this additional analysis has not yet been implemented. Material footprints would better represent the material standard of living that can be achieved in various countries and regions in different scenarios.

Table 2. Material flows, energy, and greenhouse emissions in relation to GTEM sectors.

CATEGORY	PRODUCING SECTORS	RECEIVING SECTORS
MATERIAL FLOWS		
Biomass	Crops (including biofuels)	All
	Livestock	All
	Other animals and fishing	All
	Forestry	All
Fossil Fuels	Coal	All
	Oil	All
	Gas extraction	All
Metal ores	Other mining	Iron and steel
	Other mining	Nonferrous metals
Minerals	Other mining	All other (NMM)
ENERGY AND EMISSIONS		
Primary energy	Composite from coal, oil, gas and electricity	All
GHG emissions (CO_2e)	Composite from all sectors other than manufacturing, processed food and services	Not applicable

2.3 Modeling of resource efficiency measures

The modeling explores potential improvements in resource efficiency (lower resource intensity and slower growth in natural resource extraction) through three measures. Technical resource innovation and improvements (RII) reduce the quantity of resource input required for a given volume of output. A resource extraction tax (RTAX) increases the price of natural resources relative to other inputs. Third, an exogenous resource demand shift (RDS) shifts the demand curve towards the origin. The RDS mimics the effect of changes to regulations, planning and procurement policies that seek to progressively lower resource intensity while maintaining or improving the services or amenity (such as the space and comfort provided by buildings).

The three types of measures have very different impacts on natural resource extraction, resource prices, investment and overall economic activity: see Table 3. RII reduces prices and boosts economic growth, but has only very modest impacts on extraction volumes, since lower unit costs induce higher direct and indirect natural resource use. RTAX increases prices and slows the growth of natural resource use, and also lowers the rate of economic growth. RDS reduces prices and the volume of extractions modestly, and relatively evenly, with a positive second-round impact on economic activity through increased investment (due to reduced expenditure on consumption of materials-based goods and services). The measures also impact differently across natural resource categories (biomass, fossil fuels, metal ores, and non-metallic minerals).

Crucially, these different patterns imply that the physical effectiveness and economic impacts of real-world resource-efficiency initiatives will depend on the mix, their respective intensities and detailed design of the measures employed. While we find that resource efficiency boosts economic growth and provides net economic benefits, it is possible that some resource-efficiency strategies could slow growth and result in net economic costs in some circumstances.

Table 3. Impacts of resource efficiency components on global resource extraction (DE), resource prices, investment and economic activity (GWP) in 2050. Deviation from Existing Trends (H3).

	Resource extraction (DE)	Quantity, non-fossil resources	Price, non-fossil resources	Investment	Economic activity (GWP)
	Deviation from Existing Trends (H3)				
Innovation (RII)	–1.3%	–1.5%	–0.9%	+4.6%	+8.8%
Extraction Tax (RTAX)	–8.3%	–5.9%	+25.9%	–5.0%	–4.2%
Demand Shift (RDS)	–8.4%	–8.7%	–11.7%	+7.6%	+6.2%
Combined effect (E3 vs H3)	**–17.4%**	**–16.1**	**+10.7%**	**+8.1%**	**+6.2%**

2.4 Detailed description of resource efficiency measures

Resource Innovation and Improvements (RII). This mechanism imposes sector-specific reductions in the natural resource inputs required to produce a given economic output, for selected basic processing and downstream production sectors. The size of the efficiency improvement is based on a review of currently visible cost effective potential for non-renewable resources, implemented over 20 years from 2020, and then continuing at the same rate to 2050. The average cumulative improvement in resource intensity from 2020 to 2040 is shown in Tables 4 and 5. This reduces the long-term cost of natural resource inputs to final products, and thus provides incentives for increased natural resource use (all else equal) if implemented in isolation. We find this rebound effect almost entirely offsets the initial efficiency effects, resulting in a net reduction of 1.7% in overall resource extraction in 2050 relative to existing trends.

Table 4 Assumed efficiency improvement in basic material sectors: Reduction in raw material input required to produce a unit of basic materials output, 2020–2040.

	EFFICIENCY IMPROVEMENT BY BASIC MATERIALS OUTPUT SECTORS				
	Forestry	**Non-metallic minerals**	**Iron and Steel**	**Nonferrous metals**	**Chemicals, rubber, plastics**
Materials produced	Wood and paper	Cement, sand, gravel	Ferrous metals	Nonferrous metals (aluminum, copper etc.)	Chemicals, rubber, plastics
Weighted sector improvement	1%	1%	9%	26%	1%
	EFFCIENCY IMPROVEMENT BY DOWNSTREAM ACTIVITIES (ROWS) FOR EACH OUTPUT SECTOR (COLUMNS)				
Vehicles	-	-	33%	33%	1%
Machinery and durables	-	-	20%	20%	1%
Other manufacturing	1%	-	33%	33%	1%
Buildings and infrastructure	1%	1%	0%	20%	1%

Table 5 Assumed efficiency improvement in downstream basic material sectors: Reduction in basic material inputs required to produce a unit of manufacturing or construction output, 2020–2040.

INPUT SECTOR	EFFICIENCY IMPROVEMENT BY DOWNSTREAM OUTPUT SECTORS (weighted sector improvement)	
	Manufacturing	**Construction**
Forestry	82%	0%
Iron & steel	56%	39%
NFM	35%	0%
Chemicals	0%	0%

INPUT SECTOR	EFFCIENCY IMPROVEMENT BY ACTIVITIES WITHIN DOWNSTREAM OUTPUT SECTORS (COLUMNS) IN RELATION TO INPUT SECTORS (ROWS)			
	Manufacturing			**Construction**
	Vehicles	Machinery and durables	Other	Buildings and infrastructure
Forestry	-	-	82%	-
Iron & steel	67%	52%	41%	39%
NFM	67%	52%	-	-
Chemicals	-	-	-	-

Resource Extraction Tax (RTAX). This mechanism imposes an *ad valorum* (value based) tax on all natural resource extractions, increasing from 20% 2020 to 70% 2050. Around one third of the tax is passed through to prices, increasing the average tax-inclusive price of materials by 23% per ton (and the average price of non-fossil fuel resources by 26%) in 2050, relative to existing trends, with around two thirds of the value of the tax being borne by returns to capital and labor in resource extraction sectors. This results in global natural resource extraction (DE) being 6.4% lower than existing trends in 2050, when implemented in isolation. The modeling assumes the revenue raised is returned as a lump sum transfer to households in the country of extraction, rather than being used to reduce other taxes (due to the complexity of modeling the tax arrangements of each country or regional grouping), and so does not result in a reduction in tax-related deadweight losses (referred to as a potential "double dividend" from environmental tax reform). Consistent with this, the extraction tax slows economic growth, resulting in gross world product (GWP) being 4.2% lower than in existing trends in 2050 as shown in Table 3.

Resource Demand Shift (RDS). This third mechanism mimics the effect of changes to regulations, planning and procurement policies designed to maintain or improve the services or amenity provided through natural resource use (such as the space and comfort provided by buildings) with progressively lower resource intensity over time. This is modeled as an inward shift of the demand for natural resources, reducing natural resource extraction (DE) by 7.9% and average resources prices by 11.6% in 2050, relative to existing trends. The reduction in consumption associated with lower demand for natural resources leads to an increase investment, which boosts economic growth. If implemented in isolation this demand shift would increase WGP by 6.2% in 2050, as shown in Table 3.

The combination of the three components results in resource prices around 9% higher and extraction volumes around 18% lower in 2050, comparing *Resource Efficiency* to relative to *Existing Trends*. For non-fossil fuel resources, prices are 11% higher and quantity extracted is 16% lower in 2050. Price impacts are higher for metal ores and non-metallic minerals, while prices for biomass and fossil fuels are lower than under existing trends. The pattern of change is similar for the *Efficiency Plus* (E2) scenario relative to the *Ambitious Climate* (H2) scenario, although the impact on average resource prices is lower from around 2040, reflecting the higher overall resource prices associated with more ambitious climate mitigation.

2.5 Greenhouse gas abatement

The modeling established the Existing Trends reference case by calibrating to year on year energy and industrial emissions for the RCP6.0 marker trajectory to 2050, for each greenhouse gas (Masui et al. 2011; Meinshausen et al. 2011). This is achieved through minor endogenous adjustments to emissions coefficients for each gas, applied uniformly across all sectors and regions, without the use of a carbon price. Emissions from land use change are provided from the GLOBIOM. GLOBIOM generated marginal abatement cost curves conditional on biomass demand for the SSP2 scenario. Figure 2 shows the emissions trajectory for RCP6.0 is shown relative to the likely emissions associated with the Intended Nationally Determined Commitments (INDCs) pledged at Paris.

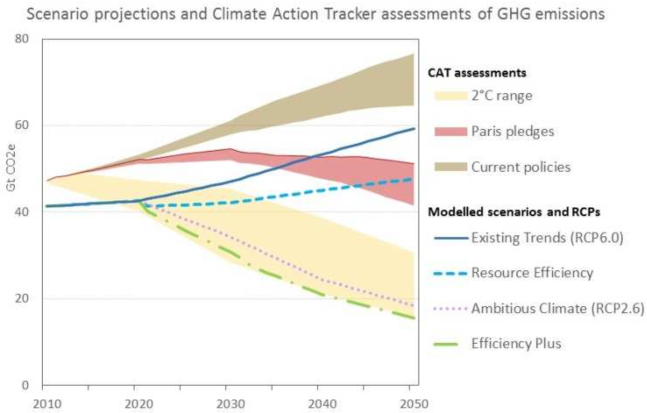


Figure 2 Emissions trajectories for four scenarios and the Paris Pledges, 2010–2050.

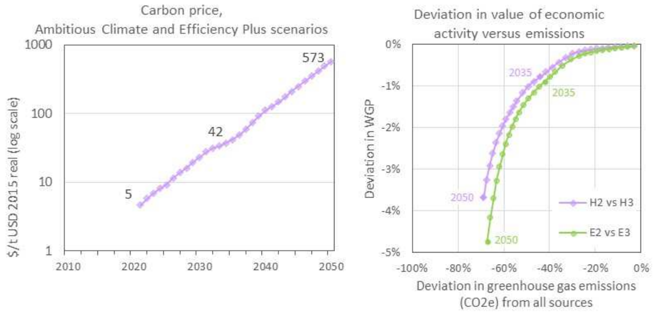
Source: Climate Action Tracker: Global emissions time series, 15 December 2015, and modeling projections

The modeling represents the stronger greenhouse abatement policies for the *Ambitious Climate* scenario as a global carbon price, applied uniformly across all countries and all industrial and energy sectors, with the price level determined endogenously to achieve the year on year emissions trajectory for RCP2.6 (as a deviation from RCP6.0). The carbon price begins at USD $5 / CO2e in 2021 and rises 18.1% per year to 2050, reaching $42 in 2035 and $573 in 2050, as shown in Figure 3. Global impacts on fossil fuel extractions, energy supply, greenhouse emissions and economic activity are shown in Figures 5-8.

While a uniform carbon price is an appropriate and transparent way of determining the extent and location of cost effective abatement, it does not account for differentiated responsibilities for emissions reductions or various forms of assistance that are expected to be provided to lower-income nations (including financial assistance, and potential trade in emissions credits). This implies the analysis is likely to understate the value of economic activity in lower-income nations (particularly ROW), perhaps materially, and may overstate the value of economic activity in high and middle future income nations.

Greenhouse gas emissions in the *Resource Efficiency* and *Efficiency Plus* scenarios arise endogenously from interactions between scenario assumptions, and are not calibrated to RCP6.0 or RCP2.6. Cumulative emissions to 2050 in the *Efficiency Plus* scenario are 9% (97 GT CO_2e) lower than in the *Ambitious Climate* scenario, implying a higher chance of limiting global warming to 2°C than under RCP2.6.

Figure 3 Carbon price and associated deviation in WGP and global emissions, 2020–2050.



2.6 GTEM-GLOBIOM linkages

For a detailed representation of GHG emissions from Agriculture, Forestry and Other Land Use (AFOLU) we rely on input from the GLOBIOM model (Havlík et al. 2011; Havlík et al. 2014). GLOBIOM is a global recursive dynamic partial equilibrium model of the agricultural and forestry sectors including bioenergy. The model simulates demand quantities, prices and bilateral trade flows for agricultural and forestry products in perfectly competitive markets at a 30 world region aggregation with spatially explicit representation of the supply side. For projections of afforestation, deforestation and forest management change, and the related CO_2 emissions, GLOBIOM is coupled with the G4M model (Gusti 2010b, 2010a; Kindermann et al. 2008; Kindermann et al. 2006). GLOBIOM was used to project the agricultural and forest sector developments under the SSP2 scenario for different levels of carbon and biomass prices and their combinations, in total 88 scenarios. The resulting "look-up table" contains information on AFOLU emissions and biomass supply, but also on food availability, agricultural and forest product markets, and land and water use. GTEM carbon prices and biomass demand for the four different scenarios were used to find matching points in the GLOBIOM solution space, and the corresponding results were added to GTEM output. "Look-up tables" have been used also in the past to link GLOBIOM with energy system models MESSAGE, POLES (Labat et al. 2015) and WITCH (Bosetti et al. 2014).

The study uses specifically generated GLOBIOM output to provide additional detail on production possibilities in the land-sector output and its associated emissions matching the GTEM global regions. A scenario data base was generated by the GLOBIOM model consisting of four scenarios to estimate response functions between food, fiber and biofuel supply and emissions from land use change given different levels of GHG prices for a range of socio-technical pathways. Variations along the commodity supply, emission reduction and socio-technical dimensions captured well the scenario ranges reported by GTEM including changes in technical efficiency in the food, forest and bioenergy sectors. Analogous linkages between spatially detailed land use and CGE models have been demonstrated at national-scale linkages in previous more comprehensive studies (Hatfield-Dodds et al. 2015a; Hatfield-Dodds et al. 2015b) but are not implemented here. Biomass projections reported in this study are from GTEM to ensure consistency across variables.

2.7 Modeling limitations

The modeling has a number of limitations that are relevant to interpreting the results.

Scenario modeling provides insights into impacts of different courses of action by comparing the results of different scenarios. Scenarios represent plausible and internally coherent future pathways, and are not predictions of the future. The analysis for this project assumes smooth future pathways, and does not account for variability and instability such as "booms and busts" in global economic markets; weather and climate related events; or wars, social unrest and geopolitical disturbances. The modeling framework reflects incremental innovation and improvements in technology as changes in the input-output ratios of each sector, but does not include endogenous mechanisms representing the possibility of innovation breakthroughs, such as the development of new types of goods and services, or step change in production processes and efficiencies.

The modeling provides projections of natural resource extraction and use by using production volume indexes of relevant sectors to weight base-year data on natural resource use and domestic material extractions. This provides an internally coherent framework for developing projections of natural resource demand and supply, accounting for interactions along the supply chain and across different sectors. The approach is novel, however, and meets a previously unmet analytical need. This implies that although the projections for the Existing Trends scenario are calibrated to historical experience, there is not a well-established literature or set of other global projections that can be used as a point of comparison in considering our results.

We consider our projections of resource efficiency potential are conservative, and can be treated as a reasonable minimum estimate of the potential to achieve reductions in natural resource use, and the associated economic benefits of greater resource efficiency. Likewise, our estimates of reducing greenhouse emissions are likely to overstate the real economic costs of shifting onto this pathway, due to limitations in the ability of models to predict the real-world innovations and breakthroughs that would be generated by concerted global efforts to reduce greenhouse emissions to less than half their current level.

The framework accounts for the economic costs of reducing greenhouse emissions but to simplify the analysis and improve transparency, the analysis does not include climate feedbacks or the benefits of avoided greenhouse emissions. The analysis will thus tend to understate the benefits of stronger action to reduce emissions. In practice, climate impacts are not expected to be globally significant before 2050, although more common and more severe extreme weather events may have significant impact in some locations or sectors.

The economic model has been calibrated to analyze greenhouse gas reduction polices and has extended technology bundles for electricity production, transport and land use. Application to modeling resource efficiency is novel, and similar detailed technology bundles for built infrastructure (residential and commercial building, transport and communication infrastructure) are being developed, but are not fully implemented in this study. This limits the depth of analysis of market and policy-driven innovations (here represented by physical innovation (RII) and demand shift (RDS)) that could have significant impacts on demand for natural resources and the potential to decouple the quantity of resource use from the services derived from that use.

3 Results and discussion

Table 6 summarizes the impacts of resource efficiency and greenhouse abatement on global resource use, prices and productivity, energy and greenhouse emissions, and the value of economic activity, for each of the four scenarios. Consistent with other studies, we find large reductions in environmental pressures and impacts can be achieved with relatively modest economic costs. Measured by deviations from the reference case, the decreases in environmental pressure range from three to twenty times larger than associated negative economic impacts (Hatfield-Dodds et al. 2015a; Hatfield-Dodds et al. 2015b; Rogelj et al. 2013). Each of the results are explored in turn below.

Table 6. Summary of global natural resource use, energy supply, greenhouse gas emissions, resource productivity and economic activity. Change from 2015–2050 and impacts in 2050.

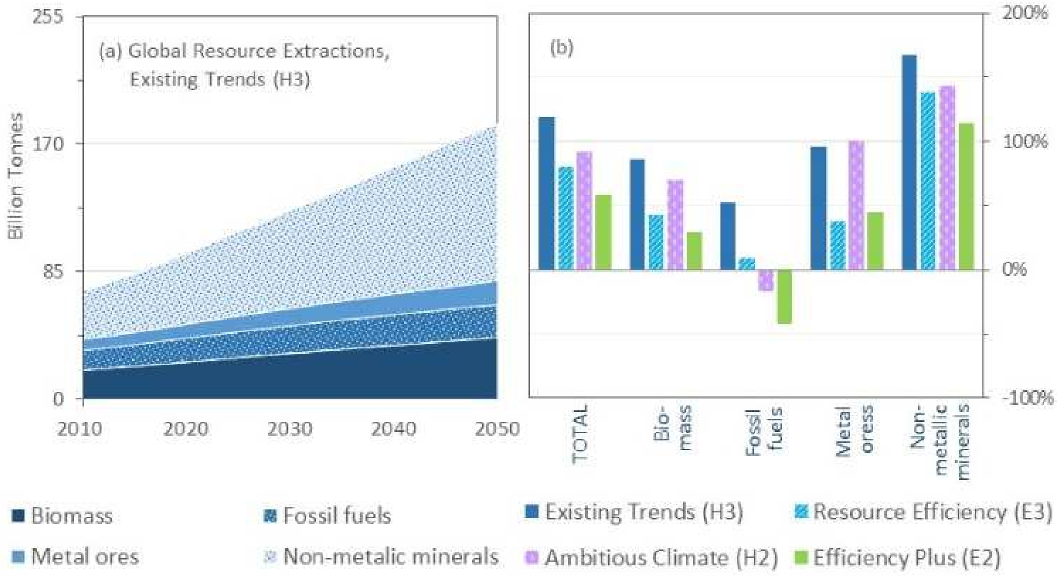
SCENARIO PROJECTIONS	Resource Use (DMC)	Price, non-fossil resources	Energy Supply (TPES)	GHG emissions (CO2e)	Resource productivity ($/kg)	Economic activity (GWP)
Global projections	*Change from 2015–2050*					
Existing Trends (H3)	119%	143%	69%	41%	–1%	116%
Resource Efficiency (E3)	81%	169%	46%	14%	27%	130%
Ambitious Climate (H2)	92%	234%	38%	–56%	9%	108%
Efficiency Plus (E2)	58%	239%	28%	–63%	38%	119%
Global per capita projections	*Change from 2015–2050*					
Existing Trends (H3)	71%	as above	33%	11%	not applicable	69%
Resource Efficiency (E3)	42%		14%	–11%		80%
Ambitious Climate (H2)	50%		8%	–66%		63%
Efficiency Plus (E2)	24%		0%	–71%		72%
MODELING TREATMENTS						
Resource efficiency measures	*Deviation from H3 or H2 in 2050*					
Resource efficiency (E3 vs H3)	–17.38%	10.7%	–13.7%	–19.6%	28.7%	6.5%
E2 relative to H2	–17.41%	1.4%	–7.6%	–15.3%	27.4%	5.3%
Abatement effects	*Deviation from H3 or E3 in 2050*					
Ambitious Climate (H2 vs H3)	–12.46%	37.4%	–18.4%	–68.9%	10.1%	–3.7%
E2 relative to E3	–12.49%	25.8%	–12.6%	–67.2%	8.9%	–4.7%
Combined efficiency and abatement effects	*Deviation from H3 in 2050*					
Efficiency Plus (E2 vs H3)	–27.70%	39.3%	–24.6%	–73.6%	40.2%	1.5%

3.1 Natural resource extractions and use

Under *Existing Trends,* we find that annual global resource extractions (DE) and resource use (DMC) increases by 119% from 2015 to 2050, from 84 to 184 tonnes. This reflects a 28% increase in population and a 72% increase in per capita resource use, from 11.5 to 19.7 tonnes per capita. *Resource Efficiency* measures reduce this resource use in 2050 by 17%, and *Efficiency Plus* by 28%. Per capita resource use would increase by 24–50% globally across the three policy scenarios.

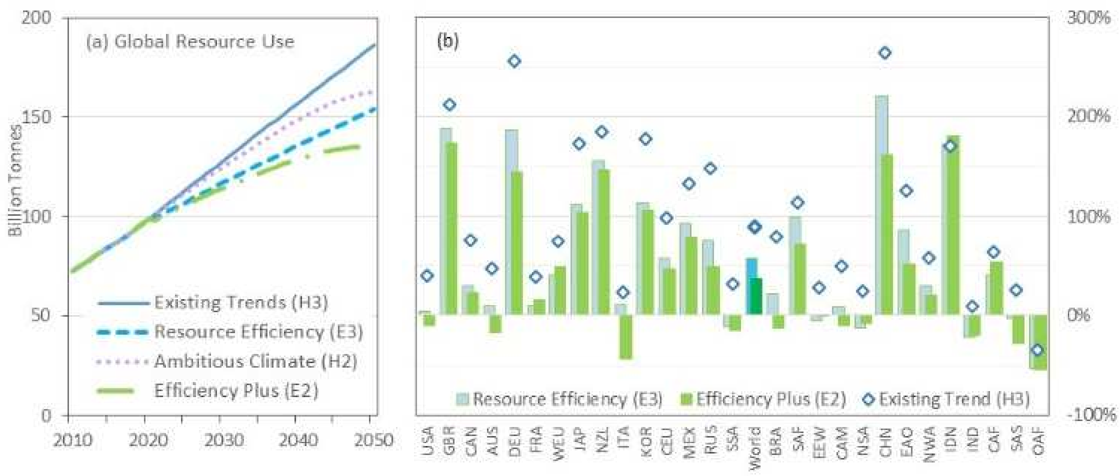
We find impacts and growth rates vary across different types of natural resources. Under *Existing Trends,* fossil fuel extractions increase 53% from 2015 to 2050, while biomass and metal ores increase 87% and 96%, and non-metallic minerals increase 168%. Under *Resource Efficiency,* extractions of the non-metallic minerals used in construction are least effected, with a 9–12% reduction in 2050 (controlling for abatement policy settings), while biomass extractions (23–24%), metal ores (28–30%) and fossil fuels (29–31%) are all significantly lower: see Figure 4.

Figure 4. Global resource extractions (DE) by four categories (biomass, fossil fuels, metal ores and non-metallic minerals) (a) 2010–2050 for Existing Trends, and (b) change from 2015 to 2050 for four scenarios. Regions are ordered by GDP per capita in 2015 from highest on left to lowest on the right for Figures 5 to 9.



Projected resource use across regions and groups of countries varies to a much greater degree, raising important questions about living standards and global equity across all the scenarios modeled. Under *Existing Trends,* per capita resource use increases by more than 25% in 24 of 28 regions, from 2015 to 2050. However, that average growth disguises a wide range between regions. Per capita resource use grows around twice the global average rate in the BRICS countries (Brazil, Russia, India, China, and South Africa), yet at only half the global average rate in low-income nations (Rest of World, ROW). This gap reflects the higher rates of GDP growth for the BRICS countries, and their diminishing reliance on resource exports. Under *Efficiency Plus*, resource use slows by around two thirds, with the 25% growth mark being reached in only 15 regions, and resource use *falling* by more than 25% in three regions: see Figure 5. While impacts on ROW regions are close to the global average, low underlying growth sees per capita resource use and energy supply rising by only 6–7% initially, and then drifting down to near current levels by 2050 (with resource use 3% higher and energy supply 2% lower than 2015 levels).

Figure 5. Global resource use (DMC) (a) 2010–2050 for four scenarios, and (b) change in per capita emissions from 2015 to 2050 for three scenarios, world and 28 regions.



Natural resource productivity ($ GDP per kg of resource use) is stable globally under *Existing Trends*, falling 1% from 2015 to 2050, and changes less than +/- 25% in 15 of 28 regions over this period. This is consistent with recent findings that embodied resource use, i.e. the material footprint per dollar of GDP, has been essentially constant historically across income levels, rather than declining per dollar as GDP per capita rises, with the apparent declines in territorial resource use (DMC) per dollar arising through high-income nations "outsourcing" more material-intensive activities to lower-income nations (Wiedmann et al. 2015).

3.2 Interactions with greenhouse gas abatement and environmental performance

Ambitious abatement increases the impact of resource efficiency measures, together achieving 1.4 times the gain in resource productivity (+40% vs +29%), 1.6 times the reduction in resource use (–27% vs 17%), and 1.8 times the reduction in energy use (–25% vs –14%) relative to resource efficiency alone.

The *Resource Efficiency* scenario sees a relative decoupling of energy from greenhouse emissions, with global fossil fuel extractions and greenhouse emissions increasing 9% and 14% while energy supply increases 46% to 2050. Ambitious abatement results in an absolute decoupling of energy from greenhouse emissions, however, with fossil fuel extractions and greenhouse gas emissions falling 17% and 56% respectively while energy supply increases 69%: see Figure 6 and Figure 7. Together, the *Efficiency Plus* scenario sees fossil fuel extractions and greenhouse emissions fall to 43% and 63% below 2015 levels (62% and 72% below *Existing Trends*) in 2050. Ambitious abatement measures also boost metal ore use modestly (3%) in 2050 relative to *Existing Trends*.

Figure 6. Global energy supply (TPES) (a) 2010–2050 for four scenarios, and (b) change in per capita energy supply from 2015 to 2050 for three scenarios, world and 28 regions.

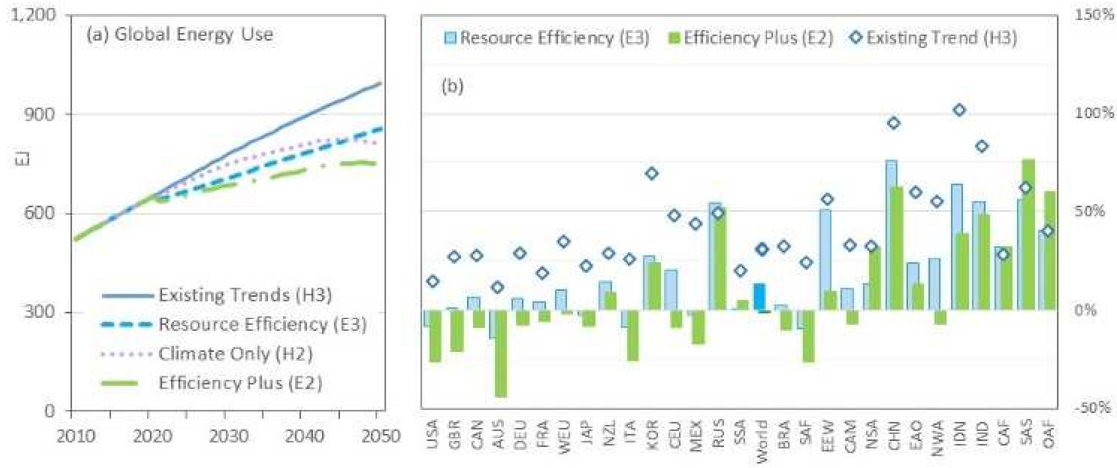
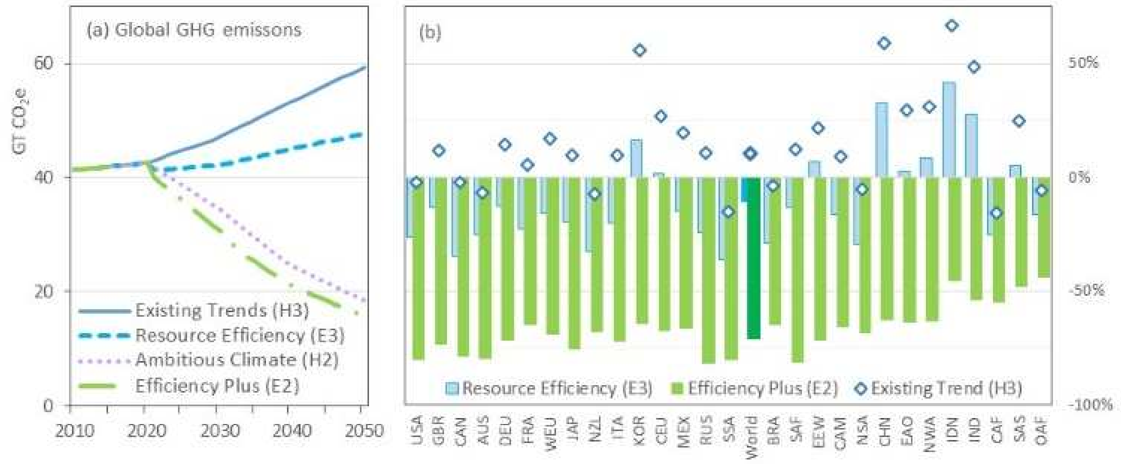


Figure 7. Global greenhouse gas emissions (a) 2010–2050 for four scenarios, and (b) change in per capita emissions from 2015 to 2050 for three scenarios, world and 28 regions.



3.3 Impacts on economic performance

We find substantial potential for reductions in resource use that are "efficient" from both a technology and an economic perspective (UNEP 2016) – that is, they reduce environmental pressure while increasing incomes and economic growth. Resource efficiency measures increase the value of economic activity in 2050 by 5–6%, and boost global resource productivity 27–29% relative to *Existing Trends*. This win-win outcome contrasts with *ambitious abatement*, which boosts resource productivity 9–10% but slows the rate of economic growth and reduces the gross value of global economic activity in 2050 by 4–5% when comparing *Ambitious Climate* relative to *Existing Trends*. Over the very long run, greenhouse abatement would be expected to boost economic growth due to avoided climate damages after 2050 (Stern 2008).

When implemented in combination, we find the economic benefits of *Resource Efficiency* outweigh the near-term economic costs of *Ambitious Climate*: global economic activity rises by 1% even while shifting to a 2°C climate trajectory: see Figure 8, Figure 9.

Figure 8. Global economic activity (GWP, GDP) (a) 2010–2050 for four scenarios, and (b) change in GDP per capita from 2015 to 2050 for three scenarios, world and 28 regions.

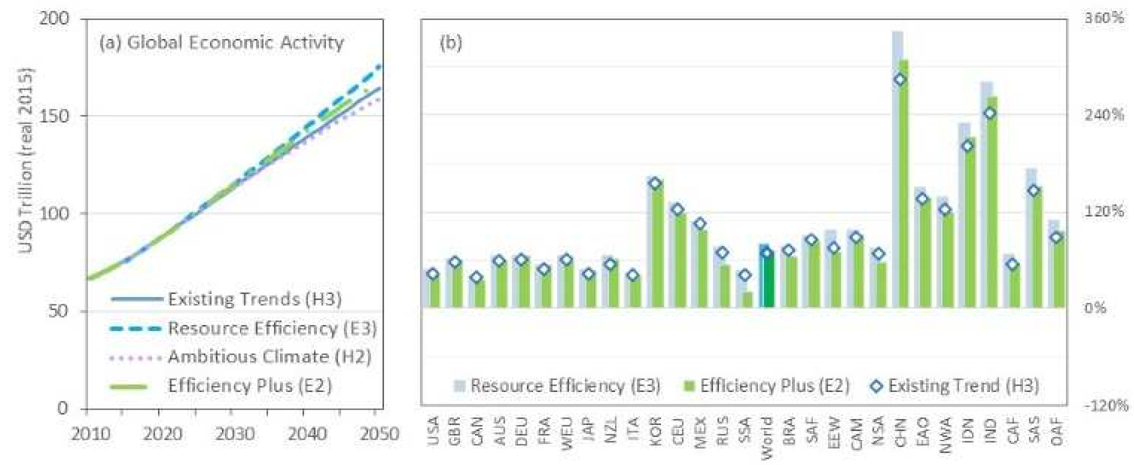
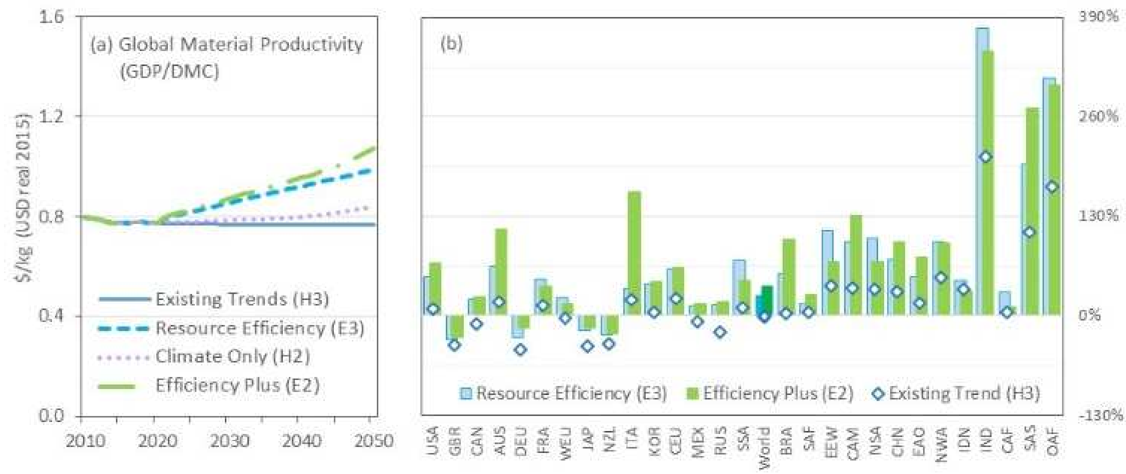


Figure 9. Global natural resource productivity (GDP/DMC) (a) 2010–2050 for four scenarios, and (b) change from 2015 to 2050 for three scenarios, world and 28 regions.



3.4 Geopolitics and the distribution of impacts across nations

Little in the projections suggest that any scenario, on its own, will see a dramatic reduction in global economic inequality. However, there is an opportunity to leverage differences the political economy of resource efficiency and greenhouse abatement, in support of globally beneficial and equitable outcomes.

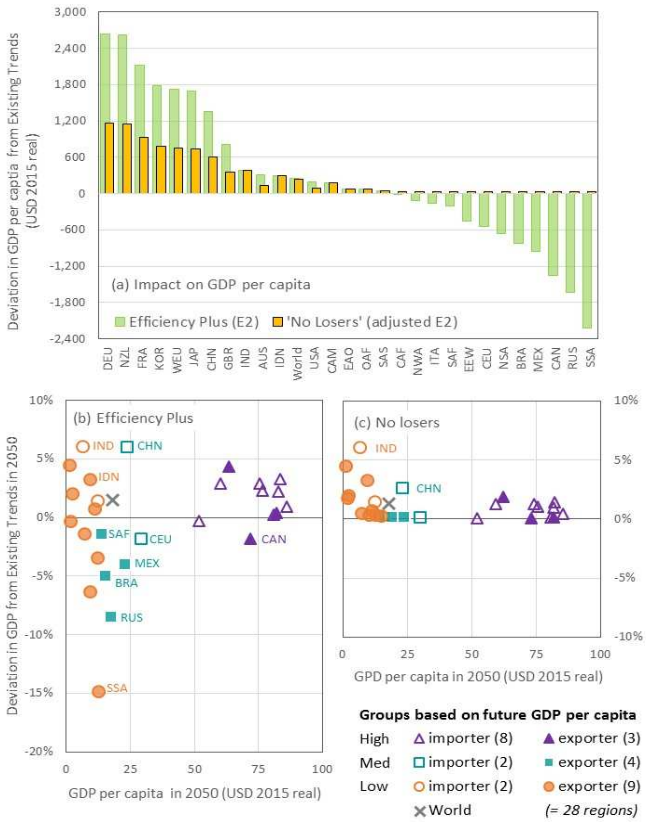
Stronger per capita economic growth in low and middle income nations reduces the ratio of GDP per capita of the highest population decile to the lowest decile from 48:1 in 2015 to 39:1 in 2050. While widespread increases in regional incomes would help reduce poverty, in 2050 around 27% of people live in regions (CAF, SAS, OAF) with per capita GDP of $4–7 per day, a subset of whom would be at risk of living in extreme poverty.

The political economy of resource efficiency and greenhouse abatement are fundamentally different. Resource efficiency can be implemented at national scale without global action, to provide near-term economic gains to implementing firms and nations. In practice, global learning may enhance the net benefits achieved, and might create incentives to position as “second movers” (Lieberman and Montgomery 1998), but we have not modeled this effect. By contrast, greenhouse abatement is a global public good, with very long lag times between nations incurring the incremental costs of emissions reductions and receiving the non-excludable shared benefits of avoided climate damages (Stern 2008). The scale, timing and distribution of avoided damages across nations and sectors is also quite uncertain (Leclère et al. 2014).

Our results suggest that the benefits of resource efficiency could be harnessed to ease the global political economy of avoiding dangerous climate change. We find that the *Efficiency Plus* scenario would provide net economic gains to 17 of 28 regions, accounting for two thirds (66%) of global population and five sixths (85%) of greenhouse gas emissions in 2050, and losses to the other 12 regions. (This result does not include any economic benefits of avoided climate change.) The regions that benefit are largely high-income nations and/or net resource importers (13 of 17), with five relatively low-income net exporters also benefiting: see Figure 10. Disadvantaged regions include South America, Russia, Mexico, Brazil, South Africa, Central Europe, Eastern Europe and West Asia, for whom global resource efficiency would dampen demand for their exported resources.

Fully compensating the net economic losses of the disadvantaged regions would require 30% of total net gains, or 40% of net gains by high and medium income nations. Figure 10 shows the impact of a grand global deal to use the gains of resource efficiency to enable a 2°C emission trajectory. This illustrative “no loser” approach involves applying 50% of the potential net economic benefits of high and middle income nations to ensure that no region is worse off than they would be under *Existing Trends*, allowing a $34 per capita “safety margin” to recognize that perfect targeting of compensation is impractical. This imagines that high and middle income nations are willing to forgo some potential gains in order to realize some gains in practice. The illustrative deal (Zenghelis and Stern 2009) would address the economic disadvantages of global resource efficiency to resource exporting nations and, at least in part, the lack of differentiated emissions targets and associated global emissions trading in the *Ambitious Abatement* scenario (see SI-4). It would see no nation worse off, and nations would be expected to be better off once the real, but hard to model (Stern 2013; Fisher and Le 2014), long run benefits of avoided climate change are accounted for.

Figure 10. Impact on economic activity (GDP per capita) for 28 regions in 2050, (a) $ impact per capita by population, and percentage impact by income level for (b) Efficiency Plus and (c) No Losers illustrative scenario.



2 Concluding comments and policy insights

The analysis and results presented underpin several important and novel findings.

First, we demonstrate a practical way to use existing computable general equilibrium (CGE) models to generate material use projections for major categories of natural resources and related accounting identities, including domestic extraction (DE), domestic material consumption (DMC), and physical trade balance (PTB). This method can easily be replicated by other modeling groups, building on the strengths and track record of different models.

Second, we find that different potential approaches to promoting resource efficiency could have very different effects on the quantity and price of resources, with different second-round effects on consumption, trade, investment, and the value of economic activity. Here we find that the rebound effect could significantly reduce the aggregate resource savings from technical (engineering-focused) improvements in resource efficiency, if used in isolation, due to the increased economic demand induced by reduced unit costs. By contrast, a resource extraction tax does not induce this rebound effect, but slows economic growth and reduces the value of economic activity, all else equal.

Third, we find substantial potential for economically attractive resource efficiency. In particular, we find a plausible illustrative mix of resource efficiency measures could reduce global resource extractions by 17% and greenhouse gas emissions by 15–20% while increasing the value of economic activity by 5–6% in 2050. We also report impacts on categories of resources (such as biomass and fossil fuels), resource prices, energy supply, and material productivity, and the distribution of these impacts across 28 countries and regions.

Fourth, we find substantial synergies between resource efficiency and greenhouse abatement, delivering larger reductions in environmental pressures and avoiding negative impacts on the value of economic activity. Here we find that the economic benefits of resource efficiency more than offset the near-term costs of shifting to a 2°C emissions pathway, resulting in emissions in 2050 well below current levels, slower growth in resource extractions, and faster economic growth. We find the *Efficiency Plus* scenario increases the value of global economic activity by 1% in 2050, relative to *Existing Trends*, providing global benefits of USD $2.4 trillion – before accounting for the value of reduced future climate risks and damages.

While the study covers an important subset of the challenges involved in transitioning to a more sustainable, secure, and inclusive world, it does not address all aspects. In particular, we find only modest reductions in global poverty, with 2.5 billion people living in countries with per capita GDP of $4–7 per day and per capita resource use of 2–4 tonnes per year across all scenarios in 2050. This draws attention to the need to develop methods for assessing deeply integrated approaches to meeting the full set of Sustainable Development Goals (SDGs) (Sachs 2012; UN 2015).

Fifth, against this backdrop we illustrate how our results can be used to understand and respond to the political economy of global action on resource use and climate change, as a key element of the SDGs. We find that the *Efficiency Plus* scenario provides net economic benefits to 61% of regions, accounting for 66% of global population in 2050. Disadvantaged regions are typically net resource exporters, with low or medium GDP per capita in 2050. Building a consensus for action through offsetting these losses (relative to *Existing Trends*) would take 30–50% of the potential gains but, we argue, would greatly increase the likelihood of these gains being realized in practice.

Overall, we find resource efficiency provides significant win-win economic and environmental gains, and offers a pro-growth pathway for limiting climate change to well below 2°C. While not a silver bullet, this suggests resource efficiency could greatly ease the politics of achieving sustainability.

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