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Economic impacts of climate mitigation: Health co-benefits and agricultural impacts

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Resumen Tesis Doctoral
Economic impacts of climate mitigation: Health co-benefits and agricultural impacts/Impactos económicos de la mitigación del cambio climático: co-beneficios en términos de salud y efectos en los sistemas agrícolas
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En los últimos años la comunidad científica ha demostrado los efectos negativos del cambio climático, evidenciando una necesidad urgente de acción. El Acuerdo de París, aprobado en 2015 por la comunidad internacional, establece un límite en el aumento de la temperatura por debajo de los 2°C para final de siglo y hace un llamamiento a limitar este aumento a 1.5°C. Sin embargo, los planes de mitigación presentados por cada país (Nationally Determined Contributions), no alcanzarían los objetivos establecidos, por lo que, durante los próximos años, deberán incrementar la ambición. Además, existen maneras muy diversas de alcanzar los objetivos mencionados con implicaciones significativas en distintas esferas (economía, energía, uso de suelo…), generándose unos co-efectos que no suelen integrarse en el diseño de las políticas climáticas. Esta tesis doctoral se centra en los efectos en términos de salud pública y en los impactos en los sistemas agrícolas derivados de la contaminación atmosférica en el contexto del cambio climático.

La contaminación atmosférica es uno de los principales factores de riesgo sobre la salud a nivel mundial, especialmente en los países en desarrollo. De acuerdo con la Organización Mundial de la Salud (OMS), las muertes prematuras derivadas de la contaminación alcanzan los 7.2 millones, de las cuales 3-4 millones se atribuyen a la contaminación ambiental. Los contaminantes más perjudiciales para la salud humana son las partículas finas ($PM_{2.5}$) y el ozono (O_3), causando enfermedades relacionadas con los sistemas respiratorio y cardiovascular. La emisión de estos contaminantes suele estar relacionada con la emisión de gases de efecto invernadero (GEI) por lo que las acciones para combatir el cambio climático reducirían los impactos sobre la salud y los sistemas agrícolas derivados de la contaminación.

En este contexto, el primer objetivo de esta tesis es el desarrollo de un marco integrado de modelización que permita comparar los co-efectos de distintos escenarios climáticos, mediante la conexión de un modelo de análisis integrado (*Global Change Assessment Model, GCAM*) con un modelo de contaminación atmosférica (*TM5-FASST*) y con distintos métodos de valoración económica. Esta combinación de herramientas permite estimar los impactos de la contaminación sobre la salud y los sistemas agrícolas hasta final de siglo de distintos escenarios climáticos, lo que añade una dimensión adicional al análisis de coste-eficiencia de las políticas de mitigación que podría ser de interés para los distintos tomadores de decisiones.

El segundo objetivo de esta tesis doctoral es aplicar dicho marco integrado de modelización en diferentes casos de estudio, con diferentes políticas climáticas. Primero, el capítulo 2 muestra los impactos de la contaminación atmosférica en los sistemas agrícolas en un escenario en el que no se establece ninguna política climática. Después, el objetivo del capítulo 3 es analizar los resultados de aplicar una política que consiste en la eliminación de los subsidios a las energías fósiles en la Unión Europea y la utilización posterior de estos recursos para financiar las energías renovables (solar fotovoltaica). Esta política es necesaria para la transición dado que los

subsidios a las energías fósiles hacen que disminuya la inversión en energías renovables y además distorsiona la competencia. Sin embargo, debido a la magnitud de los subsidios en Europa, los resultados muestran que las implicaciones en términos de contaminación atmosférica son reducidas. Por lo tanto, partiendo de la idea de que serán necesarias políticas más restrictivas de mitigación para generar importantes efectos sobre la contaminación atmosférica, los siguientes capítulos analizan los co-beneficios en términos de salud de escenarios de mitigación basados en el cumplimiento de Acuerdo de París (2°C y 1.5°C). En este sentido, se analizan diferentes opciones tecnológicas y de reparto de los esfuerzos de mitigación entre países para alcanzar los objetivos climáticos. Estos análisis demuestran que, a nivel global, en cualquiera de los escenarios de mitigación propuestos, los co-beneficios en términos de salud superan los costes de implementación de la política climática, especialmente en países en desarrollo. Estos resultados tienen una implicación directa en el análisis coste-beneficio de cualquier política climática y en el diseño de las estrategias de mitigación. A continuación, los siguientes sub-apartados muestran un resumen de los capítulos desarrollados durante esta tesis doctoral.

Estimación de los daños en los sistemas agrícolas derivados del ozono

El ozono troposférico, formado por la reacción de los gases precursores (metano u óxidos nitrosos) con la radiación solar, es el contaminante más perjudicial para los sistemas agrícolas. La exposición de la vegetación a altos niveles de este contaminante genera distintos daños como necrosis, clorosis, alteraciones en el genoma o reducción en la fotosíntesis. El segundo capítulo de esta tesis doctoral estima los daños en la productividad agrícola y los efectos económicos derivados del ozono para un escenario en el que no existe ninguna política climática.

Los niveles actuales de concentración de ozono exceden en muchos lugares los valores límite, lo que genera pérdidas significativas en la productividad. Este análisis muestra los daños económicos, actuales y futuros, para distintos cultivos, utilizando precios regionales y dinámicos en el tiempo. Además, la re-incorporación de los coeficientes de daño en el modelo de análisis integrado (GCAM) permite estimar efectos a futuro en los mercados agrícolas.

Para la proyección de los daños, dentro del marco de modelización desarrollado, se ha asumido que el progreso tecnológico implícitamente hará que las emisiones de gases precursores disminuyan en el futuro, también en un escenario en el que no se especifica ninguna política climática. Se estima que los niveles de ozono en el futuro serán inferiores a los actuales en la mayoría de regiones del mundo, con alguna excepción como India, donde el incremento esperado de emisiones de metano (relacionadas con el aumento poblacional) hace que los niveles de ozono en el futuro sean superiores a los actuales con efectos más notables en las cosechas. Los resultados muestran que, a nivel global, los daños económicos en los sistemas agrícolas derivados del ozono podrían alcanzar los 5041-5987, 9780-18830, 6726-10536 y 10421-12461 millones de euros anuales para el maíz, la soja, el arroz y el trigo, respectivamente, durante el horizonte temporal analizado. Estos efectos tendrían implicaciones directas en los precios y en los niveles de producción, e indirectas en los usos de suelo y en la seguridad alimentaria, especialmente en los países en desarrollo.

Además, los daños en la productividad calculados tendrían efectos significativos en los mercados agrícolas ya que las demandas de cada región y cultivo responden de manera distinta a dichos daños. Esto supondría una re-distribución de la producción de cultivos entre las distintas regiones, con sus correspondientes cambios en usos de suelo. Así, los niveles globales de producción de ciertos cultivos podrían aumentar hasta casi el 1% (soja), mientras que el daño económico podría variar hasta un 3.84% (arroz). Desde un punto de vista regional, India mostraría la mayor variación en la producción (arroz, 6%) y en los daños económicos 1.67% (trigo). Estas variaciones demuestran la importancia de incorporar los impactos del ozono en los distintos ejercicios de modelización y en los escenarios utilizados.

Implicaciones del reciclado de los subsidios a las energías fósiles a la promoción de energía solar: Un caso de estudio para la Unión Europea

La eliminación de los subsidios a las energías fósiles y su posterior "reciclado" para la promoción de energías renovables como la solar es una política necesaria para la mitigación del cambio climático, ya que los subsidios distorsionan la inversión en energías limpias. Es por esto que debería considerarse una medida prioritaria en cualquier estrategia de mitigación.

El objetivo del capítulo 3 de esta tesis doctoral es examinar las implicaciones de la implementación de esta política en la Unión Europa en términos de contaminación atmosférica y otros efectos adicionales como la reducción de emisiones de CO_2 o penetración de las energías renovables. Los resultados muestran que el reciclado de los subsidios desplazaría el carbón del sistema energético, contribuyendo a la reducción de las emisiones tanto de CO_2 como de contaminantes atmosféricos. Sin embargo, los posibles co-beneficios derivados de la contaminación estarían directamente relacionados con el tipo de tecnología que sustituya al carbón.

Concretamente, el estudio muestra que la eliminación de subsidios a las energías fósiles, reduciría las emisiones de CO_2 hasta un 1.8% en 2030 y, además, si estos subsidios se reinvierten en la promoción de la energía solar fotovoltaica, la reducción aumentaría hasta un 2.2%. Por otro lado, habría una reducción de algunos contaminantes como el SO_2 (3%). Sin embargo, los co-beneficios en la salud no serían significativos, principalmente por dos razones. Por un lado, las variaciones absolutas de los contaminantes no son suficientemente importantes, siendo todas inferiores al -5%. Por otro lado, dado que el carbón desplazado sería sustituido en parte por biomasa (sobre todo fuera del sector eléctrico), la reducción de algunos contaminantes podría compensarse con el incremento de otras sustancias como el monóxido de carbono (CO) o el carbono orgánico (OC), directamente relacionadas con el uso de biomasa.

La principal conclusión de este análisis es que, a pesar de ser una política necesaria y con efectos positivos en algunos ámbitos, los efectos que podemos esperar en términos de salud y sistemas agrícolas no son significativos por la baja variación en las emisiones de los contaminantes atmosféricos. Para poder obtener co-beneficios significativos, se necesitan políticas más restrictivas y con objetivos climáticos más ambiciosos, como se analiza en los siguientes capítulos de la tesis doctoral.

Co-beneficios en términos de salud y costes de mitigación del Acuerdo de París: un ejercicio de modelización

La contaminación atmosférica y el cambio climático son dos problemas que están directamente relacionados ya que las políticas para reducir las emisiones de gases de efecto invernadero suelen reducir las emisiones de contaminantes locales. Por lo tanto, los objetivos de mitigación definidos en el Acuerdo de París generarían importantes co-beneficios para la salud. Sin embargo, uno de los principales desafíos de este acuerdo es la distribución de los esfuerzos de mitigación entre los distintos países, ya que la literatura muestra que la ambición del objetivo está directamente relacionada con la dificultad para la distribución de esfuerzos. Además, también se ha evidenciado que los planes de mitigación presentados por los distintos países no van a ser suficientes para alcanzar los objetivos establecidos. En este contexto, el capítulo 4 de la tesis doctoral compara los co-beneficios en términos de salud y los costes de mitigación relacionados con alcanzar los distintos objetivos de temperatura establecidos en el Acuerdo de París (2°C y 1.5°C) aplicando distintos criterios de distribución del esfuerzo de mitigación. Estos criterios están basados en principios como la capacidad de mitigación o la equidad.

A pesar de que la relación entre cambio climático y contaminación atmosférica queda bien demostrada en la literatura científica, no existen muchos estudios que, utilizando un marco integrado de modelización, comparen los costes de la mitigación con los beneficios económicos de la reducción de la contaminación en diferentes escenarios de mitigación del cambio climático. Este capítulo demuestra que, independientemente del método de reparto del esfuerzo, la implementación de los objetivos climáticos va a generar importantes co-beneficios en términos de salud ya que, bajo ciertos supuestos, doblarían los costes de mitigación a nivel mundial. Además, se han realizado análisis de sensibilidad para distintas variables que demuestran la robustez de los resultados.

Concretamente, en valores acumulados hasta el año 2050, el ratio co-beneficios/costes de mitigación oscilaría entre 1.4 y 2.45 a nivel global, dependiendo del escenario. A nivel regional, en países como China o India los co-beneficios en términos de salud serían muy superiores a los costes de mitigación, mientras que en otras regiones como la Unión Europea o EEUU cubrirían alrededor de un 7-84% y 10-41% de los costes de mitigación respectivamente, dependiendo del criterio de distribución aplicado. Además, los co-beneficios harían que el esfuerzo extra de alcanzar el objetivo de 1.5°C fuese económicamente rentable en India y en China, ya que, durante el periodo analizado, se generaría un beneficio marginal acumulado neto de 3.28-8.4 y 0.27-2.31 trillones de dólares respectivamente.

Co-beneficios en términos de salud y costes asociados a escenarios de mitigación con distintos niveles de desarrollo tecnológico

En la misma línea que el capítulo anterior, este estudio compara los co-beneficios en términos de salud a nivel global y regional con los costes de mitigación relacionados con el objetivo de incremento de la temperatura de 2°C en distintos escenarios basados en diferentes niveles de desarrollo de tecnologías claves para la mitigación del cambio climático. Estos escenarios tecnológicos están basados en el quinto informe de valoración del Panel Intergubernamental del Cambio Climático (IPCC AR5) y asumen distintos niveles de desarrollo de tecnologías como la bioenergía, la generación nuclear o la captura y almacenamiento de CO_2 (CCS).

El análisis demuestra que los co-beneficios en términos de salud serían significativos independientemente del escenario tecnológico escogido. Las muertes prematuras derivadas de la contaminación atmosférica en los escenarios de mitigación se reducirían entre un 17% y un 23% comparado con un escenario sin política climática. Por otro lado, el ratio de co-beneficios/costes de mitigación varía significativamente dependiendo del escenario tecnológico. Así, si el objetivo se alcanzase con todas las tecnologías disponibles (sin establecer explícitamente ninguna limitación), los co-beneficios doblarían el valor de los costes (ratio de 2.19), mientras que en el caso de establecer un límite en el uso de la biomasa de 100 exajulios a nivel mundial, el mismo ratio se reduciría hasta 1.45. En cuanto a resultados regionales, India y China, debido a su grado de desarrollo y a su densidad de población obtendrían los beneficios más significativos. Por último, cabe destacar que los resultados a medio plazo (2030) serían mayores que los obtenidos a largo plazo, lo que hace aún más atractiva la acción temprana.

Conclusiones

El objetivo de esta tesis doctoral ha consistido en evaluar los impactos en la salud y la agricultura derivados de la contaminación atmosférica en diferentes escenarios climáticos. Para ello, se ha desarrollado una innovadora metodología que conecta secuencialmente un modelo de análisis integrado, un modelo de calidad de aire y distintos métodos de valoración económica. La aplicación del marco integrado de modelización desarrollado a diferentes escenarios ha demostrado la importancia de incorporar estos co-efectos en el análisis de las políticas climáticas.

Sin embargo, las estimaciones basadas en modelos tienen una serie de limitaciones y supuestos. La tesis doctoral también muestra que la definición de los escenarios de mitigación va ser un factor que afecte directamente a los resultados obtenidos. Por este motivo, este análisis tiene un grado de incertidumbre que es necesario considerar para poder interpretar correctamente los resultados. Aun así, los modelos de análisis integrados son herramientas extremadamente útiles, pues permiten comprender mejor la complejidad del reto climático, proporcionando información relevante para los diferentes agentes involucrados en la lucha contra el cambio climático. Es por esto que organismos como el Panel Intergubernamental del Cambio Climático, la Agencia Internacional de la Energía, la Comisión Europea o la Organización Mundial de la Salud utilizan este tipo de herramientas de manera habitual en los procesos de toma de decisiones. Además, la comunidad científica trabaja asiduamente en el desarrollo y refinamiento de estas herramientas desde un enfoque trans-disciplinar, habiendo conseguido avances significativos en los últimos años.

En definitiva, el análisis de los co-beneficios desarrollado en esta tesis doctoral muestra la importancia de abordar de una forma integrada las políticas y estrategias para el cambio climático y la contaminación atmosférica.

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OUTCOMES FROM THIS PhD THESIS

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Ongoing

"Future impacts of ozone driven damages on agricultural systems". Jon Sampedro, Stephanie Waldhoff, Dirk-Jan Van de Ven, Guillermo Pardo, Rita Van Dingenen, Maria Jose Sanz, Agustín del Prado

"Health co-benefits from air pollutant reduction through coal-fired power plant cancellations". Ryna Yiyun Cui, Jon Sampedro, Haewon McJeon, Nathan Hultman, Linlang He, Rita Van Dingenen, Ignacio Cazcarro

"A sensitivity analysis of modelling health co-benefits of global climate mitigation commitments". Tara Neville, Aneete Pruss- Ustun, Diarmid Cambell-Lendrum, Gavin Shaddick, Jon Sampedro, Anil Markandya, Rita Van Dingenen, Matthew Thomas, Arthur Wyns

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ABSTRACT

The transition to low carbon economies is one of the most urgent challenges society needs to face in order to prevent and reduce the harmful effects of climate change. Every mitigation strategy requires the energy system to be substantially transformed. Additionally, changing the energy systems has a diverse range of associated co-benefits and side effects, with substantial economic implications, that are not usually integrated in policy design.

The aim of this PhD thesis is to analyze air pollution driven co-effects of different climate change scenarios and mitigation options, with a special focus on health and agriculture by developing an innovative methodology which combines the use of an integrated assessment model (GCAM), an air quality model (TM5-FASST) and economic valuation methods.

Chapter 2 analyzes air pollution driven damages in crop yields and the resulting effects on agricultural markets of a scenario where there is no climate policy established. Afterward, Chapter 3 examines which are the implications of reverting current fossil fuels subsidies into clean solar technologies in terms of air pollution. Then, the subsequent chapters analyze health co-benefits associated to different transition pathways. While Chapter 4 estimates the potential co-benefits of achieving both the 2°C and the 1.5°C objectives following different burden-sharing criteria, Chapter 5 focuses on co-benefits associated to achieving the 2°C target under different technological scenarios.

Chapter 1

Introduction

Motivation

There is widespread agreement in the scientific community as to the harmful effects of climate change (Cook et al., 2016), and as to the need for urgent action. The Paris Agreement[1], approved by most countries around the world in 2015, seeks to limit global temperature increase in this century to less than 2°C, with "efforts to limit the temperature increase even further to 1.5°C". To that end, countries were required to define their efforts to reduce national emissions and adapt to the impacts of climate change. These efforts are known as "Nationally Determined Contributions" (NDCs), and must be updated every 5 years.

Nevertheless, the application of current NDCs is not ambitious enough to achieve the 2°C target, and the increase by the end of the century is likely to be between 2.6 and 3.1°C (Rogelj et al., 2016). Furthermore, there are several different ways to achieve long-term climate objectives with implications in many different spheres (economic, social, energy, environmental, etc.). In particular, each transition pathway has a broad range of side effects in the form of co-benefits and drawbacks that are not always integrated into climate policy design. Specifically, air pollution-driven impacts on health and agricultural systems are relevant side-effects which have not so far been addressed in an integrated framework. These effects are not usually explored by research communities, so they are not always considered by policy makers and stakeholders. It is very important to explore the extent of health and agricultural side-effects as they could be a game-changer for the cost-benefit analysis of mitigation strategies for different countries. However, assessing such side-effects is a complex challenge, as it requires the interconnection of very diverse systems such as the economy, the energy system and the composition of the atmosphere. The quantification and assessment of these side-effects in a consistent global framework lies at the heart of this PhD thesis.

According to the Global Burden of Disease study (Forouzanfar et al., 2016), air pollution is a leading risk factor to health, especially in low and middle income countries (Cohen et al., 2017). A recent report from the World Health Organization (WHO, 2018) estimates that current air pollution-driven premature deaths total around 7.2 million, of which 3-4 million are attributable to ambient (outdoor) air pollution. Furthermore, recent studies conclude that the number of deaths attributable to this cause may be substantially underestimated (Burnett et al., 2018; Lelieveld et al., 2019). Most ambient air pollution driven premature deaths can be attributed to ischemic heart disease (40%) and stroke (40%), but a significant number are also caused by chronic obstructive pulmonary disease (11%), lung cancer (6%), and respiratory infections in children (3%).

In terms of human health, the most harmful pollutants are particulate matter ($PM_{2.5}$[2]) and ozone (O_3) which are significantly determined by the emissions of various precursors[3]. The effect of these pollutants on human health has been widely evidenced in numerous studies (Apte et al., 2015 and Brauer et al., 2016 for $PM_{2.5}$; Turner et al., 2016 for O_3). Moreover, recent literature shows that air pollution has effects in previously unexplored fields such as mental health (Newbury et al., 2019) and diabetes (Bowe et al., 2018). $PM_{2.5}$ and O_3 are closely related to the use of fossil fuels, so actions to fight climate change significantly affect air pollution since they are two related hazards that usually (but not always) come from similar sources (Haines et al.,

[1] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[2] $PM_{2.5}$ are particles of 2.5 microns or less in width

[3] Sulfur dioxide (SO_2) and nitrogen oxides (NOx), ammonia (NH_3) black carbon (BC) and organic carbon (OC) are the main precursors for the formation of $PM_{2.5}$, and methane (CH_4) and NOx for O_3, but not the only ones.

2010) and sectors (Crippa et al., 2019). In recent years, a number of scientific studies have estimated current and future health costs of air pollution. For example, OECD (2016) shows that the cost of air pollution-driven health damage may range from US$18-25 trillion in 2060.

Certain inefficient policies also distort the transition and can significantly increase damage, such as fossil fuel subsidies (FFS). Even though the penetration level of renewable energy is increasing due to active political support and a substantial reduction in costs (IRENA, 2017), both developed and developing countries still subsidize fossil fuel technologies, which is inconsistent with the climate objectives defined in the Paris Agreement. A report from the International Monetary Fund (IMF, 2013) shows that FFS totaled $233 billion globally in 2013 (0.41% of global GDP), more than four times the amount of subsidies awarded to promote renewable energy. The same report states that the externalities[4] produced by the implementation of those subsidies may represent up to 5 US$ trillion, 52% of which is accounted for by air pollution-driven health impacts. Not only are FFS a regressive mechanism according to the IMF, but their phasing out and potential recycling into cleaner energy sources could entail additional benefits in terms of pollutant reduction.

Similarly, several studies focused on the health co-benefits of climate change mitigation (Vandyck et al., 2018; West et al., 2017) estimate the scale of co-benefits and evidence the need to incorporate them into policy design. However, as pointed out in the IPCC's 5th Assessment Report (IPCC, 2014), there are "large methodological differences in, for example, the type of pollutants analyzed, sectoral focus, and the treatment of existing air pollution policy regimes". Moreover, there is a gap with regard to mitigation strategies, as they do not capture the implications of different temperature targets (2°C or 1.5°C as per the Paris Agreement), technological developments or the distribution of mitigation efforts.

O_3 driven agricultural impacts are also linked to climate change mitigation strategies, since emissions of O_3 precursors are usually linked to non-renewable energy sources (Fiore et al., 2009). Actions to fight climate change usually entail significant reductions in air pollutant emissions, and thus have substantial co-benefits in terms of improvements of agricultural yield and productivity. O_3 has been identified as the most harmful element for crop yields (within the expected environmental changes), with soybeans and wheat being the crops most sensitive to it. One of the most widespread models for estimating O_3 driven crop damage is that of exposure-response functions (ERFs). ERFs calculate the relative yield losses for each crop given a preset O_3 level. Several studies analyze RYLs using ERFs at both global and regional levels (Avnery et al., 2011; Van Dingenen et al., 2009). They show that O_3 driven RYLs could be as great as 20%, depending on the crop and the region, with all the economic damage that this entails.

[4] The IMF report referenced above calls such externalities "post-tax subsidies"

Objectives

The aim of this PhD thesis is to assess air pollution-driven health and agricultural impacts and analyze their role in different climate change mitigation strategies. To that end, the first objective is **to develop an integrated modelling framework** to estimate health and agricultural impacts and their trends under different climate mitigation scenarios. In order to provide a wide perspective to policy analysis, this thesis develops a framework that combines an integrated assessment model, an air quality model, and economic valuation methods. On the one hand, integrated assessment models are used in general to compare different mitigation scenarios in terms of mitigation costs, energy mix, land use change, emissions of greenhouse gases and air pollutants, and temperature change. On the other hand, air quality models are applied to analyze the implications in terms of air quality and health and agricultural impacts of emissions of air pollutants. The combination of the two types of model enables an integrated assessment to be drawn up of the health and agricultural impacts of different mitigation scenarios. This matter needs more research effort, given its significance. Furthermore, the combination of these models with economic valuation methods enables the economic co-benefits of climate mitigation to be assessed. The Methodology subsection below provides a detailed description of this novel assessment framework.

The second objective of the thesis is to use the integrated modeling framework drawn up to **explore the co-effects of a number of climate change scenarios,** and in particular to analyze health and agricultural implications for different pathways. First, the framework is used in Chapter 2 to analyze current and future air pollution-driven effects on crop yield and agricultural markets of a scenario where no climate policy is set. Then Chapter 3 explores the potential co-benefits of a mitigation policy consisting of removing fossil fuel subsidies and recycling them to promote renewables (rooftop solar). The framework is subsequently used to analyze health co-benefits of different mitigation scenarios with more stringent climate policies. Chapters 4 and 5 explore the health co-benefits of different climate objectives (1.5°C and 2°C) under different technological scenarios and burden sharing criteria. These analyses show the extent to which side effects could play a significant role in any climate mitigation strategy set up for certain key countries.

Methodology

In order to analyze health and agricultural impacts of different climate policies, most of the studies developed during the PhD Thesis have been based on the subsequent use of two different models: The Global Change Assessment Model (GCAM) and the Fast Scenario Screening Tool (TM5-FASST)[5]. The soft-link of these two models is original and has been fully developed during this PhD Thesis. The aim of this innovative methodology is to analyze different (policy and no policy) scenarios from now to 2100, and to identify the effects of different climate policies in different areas with a focus on air pollution driven health and agricultural effects.

In this context, first, GCAM is used to quantify the greenhouse gas emissions pathways and the related mitigation costs of different scenarios. GCAM also reports, for each scenario, the emissions of air pollutants in the different regions covered by the model; this information is passed on to the TM5-FASST air quality source-receptor model, which translates emission levels into concentrations and, subsequently, into premature deaths and relative yield losses (RYLs). For health co-benefits analysis, those premature deaths are monetized using the Value of Statistical Life (VSL) approach. This method has been extended in order to incorporate morbidity effects. The details of this approach are presented in a following subsection (*economic valuation approach*).

Regarding the estimation of agricultural damages, the obtained regional, period by period emissions are fed into the TM5-FASST model, in order to measure O_3 concentration levels. To estimate the economic impacts, projected crop losses are multiplied by the agricultural market prices, obtained from GCAM for every region and period[6]. Finally, the obtained O_3 damage coefficients (per period and region) are re-set into GCAM, as exogenous yield shocks. So, it is possible to compare the outcomes of a default GCAM baseline (no O_3 effects) with the scenario where the estimated yield changes per period and region are incorporated. This innovative procedure enables to see the most important impacts in agricultural systems by including the O_3 damages into future projections. As the model is calibrated for 2010, the damages are included as yield shocks relative to that base year. However, the TM5-FASST model only calculates damage coefficients for certain categories (wheat, corn, rice and soybeans) so to omit the impacts in some other crops would distort the market. In order to avoid that inconsistency, and to expand the losses to all of the crops, a crop mapping has been developed based on their carbon fixation pathway[7].

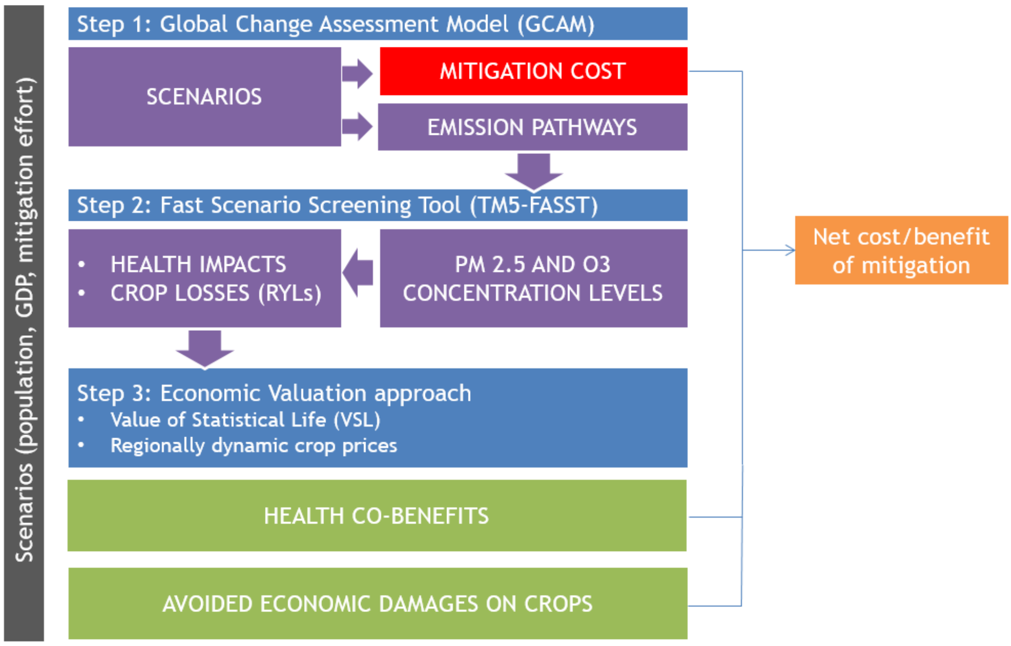
In order to consistently develop the inter-model connection, GCAM regions and crop categories have been re-scaled so they match with TM5-FASST input requirements. Annex I shows detailed information about regional disaggregation of the two models used. In addition, Annex II describes the crop mapping followed by GCAM. The following subsections provide detailed information about these models.

[5] Except for the analysis on Chapter 3, in which uniquely GCAM has been applied

[6] Literature has demonstrated that applying a current price could result in significant underestimation of economic losses (Heck et al., 1987).

[7] C3 and C4 plant species present differences in stomatal conductance and transpiration rates, which determine their sensitivity to O3 damage (Ainsworth, 2017; Knapp, 1993). Based on this criterion, the corn damage coefficient is applied to C4 classified commodities, while for C3 crops, the average damage of rice and wheat (or rice, wheat and soybean) is considered depending on the crop type classification This average includes damage coefficient from soybean for those crop groups that include legumes (f.e. MiscCrop).

Figure 1.1: Integrated modelling framework developed



Global Change Assessment Model (GCAM)

GCAM is an integrated assessment model originally developed by the Joint Global Change Research Institute (JGCRI). It is one of the four models chosen to develop the Representative Concentration Pathways (RCPs) of the IPCC's 5th Assessment Report and has participated in almost all of major climate/energy assessment over the last 20 years.

GCAM is a global dynamic-recursive partial equilibrium model with technology-rich representations of the economy, energy sector and land use linked to a climate model that can be used to explore climate change mitigation policies. The model is disaggregated into 32 geopolitical regions and operates in 5-year time steps from 1990 to 2100.

The GCAM energy system includes primary energy resource production, energy transformation to final fuels, and the use of final energy forms to deliver energy services. The model distinguishes between two different types of resources: depletable and renewable. Depletable resources include fossil fuels (coal, gas and conventional and unconventional oil) and uranium (for nuclear power); renewable resources include biomass, wind, hydropower, geothermal energy, rooftop areas for solar photovoltaic equipment and non-rooftop solar (PV and CSP).

Another important feature of the GCAM architecture is that the GCAM terrestrial carbon cycle model is embedded in the agriculture-land-use system model. Thus, all land uses and land covers, including non-commercial land, are fully integrated into the economic modelling in GCAM. This feature enables the model to include agricultural, forest, and land use (AFOLU) activities in the modelling and solving process. Moreover, this module allows the user to obtain the emissions derived from changes in land use.

Economic land use decisions in GCAM are based on a logit model of sharing (McFadden 1974) based on relative inherent profitability of using land for competing purposes. The interpretation of this sharing system in GCAM is that there is a distribution of profit behind each competing land use within a region, rather than a single point value. Each competing land use option has a potential average profit over its entire distribution. The share of land allocated to any given use is based on the probability that that use has a highest profit among the competing uses. The relative potential average profits are used in the logit formulation, where an option with a higher average profit will get a higher share than one with a lower average profit. The profit rate is the difference between the market price of the commodity on the production costs, which depend on land rent, fertilizer costs, other non-land costs and the crop yield. Crop yields in the base year (2010) are taken from a blend of FAO (2013) and GTAP (2011) data and are calibrated for each of the Agro-Ecological zones within each of the 32 regions. For the estimation of future yields per AEZ GCAM uses data from the Food and Agriculture Organization (FAO)[8].

GCAM also provides the mitigation cost of different energy and climate policies for each specific region. These costs are calculated by the model as the area below the marginal abatement cost curve. Additionally, the model reports the emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) or nitrogen dioxide (N_2O) and the main air pollutants including OC, BC, nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO) and sulfur dioxide (SO_2) which are the main precursor gases of $PM_{2.5}$ and O_3.

While emissions of air pollutants in GCAM are closely related to activity levels and fuel consumption, some level of pollution control is assumed. The emission factors decrease with GDP growth, based on the “Environmental Kuznets Curve” hypothesis, which postulates that pollution levels decline as a country becomes richer. Consequently, even if there is no climate policy, economic growth will result in a reduction of air pollution per unit of activity.

TM5-FASST Model

TM5-FASST is a global air quality source-receptor model developed by the European Commission’s Joint Research Centre (JRC) that enables users to analyze different scenarios or emission pathways and their effects in terms of human health impacts and agricultural damages. Based on meteorological and chemical information, the model analyzes how the emissions of a ‘source’ affect the ‘receptor points’ established (grid cells) in terms of concentrations, exposure and, subsequently, of premature deaths.

Following the TM5-FASST User Guide (JRC 2016), the concentrations of a given pollutant are set by a linear equation as follows:

$$C_{ij}(x,y) = c_j(y) + A_{ij}(x,y)E_i(x) \qquad (1.1)$$

This equation defines the concentration of pollutant j at receptor (cell grid) y formed from the precursor i emitted in the source x ($C_{ij}(x,y)$), as the sum of a spatial constant (c_j) plus the emission rate ($E_i(x)$) of precursor i in source x multiplied by the source-receptor coefficient (A_{ij}) between the source (x) and the receptor (y).

The source-receptor coefficient representing the different links between sources and receptors are previously calculated by applying an emission perturbation of 20% to a reference scenario in the full chemistry model (TM5) and calculating the resulting concentrations as for equation (1.1). Although the model covers the entire world in a resolution of 1 x 1 grids (100 km2), the procedure is shown here for 56 source regions. Thus, the source-receptor coefficient for each cell is defined as:

[8] All countries are assumed to have the same yield improvement rates in all AEZs. Single-country regions therefore have the same yield improvement rates in all AEZs for all crops. However, multi-country regions do have differential, AEZ-specific growth rates for each crop, as the yield improvement rates are downscaled to the AEZs prior to aggregating by GCAM regions and AEZs.

$$A_{ij}(x, y) = \Delta C_j(y)/\Delta E_i(x) \qquad (1.2)$$

Where $\Delta E_i(x) = 0.2 * e_i(x)$, with $e_i(x)$ being the emissions in the reference scenario.

It is important to note that each precursor emitted might indirectly affect the concentration of different pollutants. For example, emissions of the precursor NOx entail not only the creation of $PM_{2.5}$ in the atmosphere but also the formation O_3. For this reason, the total concentration of pollutant j at receptor y resulting from the emissions of all its precursors (i) from all sources (x) is:

$$C_j(x, y) = c_j(y) + \sum_x \sum_i A_{ij}(x, y)[E_i(x) - e_i(x)] \qquad (1.3)$$

Once the concentration levels for each region are obtained, the model calculates different effects such as air pollution direct impacts on human health and agricultural damages. The calculations of the health effects are based on the Burnett exposure-response functions (Burnett et al., 2014). The model includes the potential premature deaths derived from five sources: ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), stroke, lung cancer, and acute lower respiratory infection (ALRI). The first four are driven by $PM_{2.5}$ exposures, while ALRI is also a consequence of high concentrations of O_3. More technical features of TM5-FASST model are described in Van Dingenen et al., 2018. Regarding agricultural impacts, TM5-FASST model analyzes crop exposures to O_3 based on two different metrics: "the accumulated daytime hourly ozone concentration above a threshold of 40 ppbV (AOT40) [9]", and the seasonal mean daytime ozone concentration, M7 for the 7-hour mean and M12 for the 12-hour mean (Van Dingenen et al., 2009)[10]. Once the O_3 exposure is calculated, the model applies ERF damage functions in order to estimate the regional crop damages (for every region and period) for four significate crops: wheat, corn, rice and soybeans. Further information about the methodology can be found in Van Dingenen et al., 2009.

Economic valuation approach

Once the health and agricultural impacts are calculated, their monetization allows to develop a cost-benefit analysis that provides substantial information about the cost-effectiveness of any mitigation strategy. For the agricultural impacts, as GCAM calculates the regional agricultural prices per period, with the combined use of the models allows to estimate the economic damage by multiplying the relative yield losses (RYL) of a determined region and period with the projected production and price levels of that region and period, as summarized in the following equation:

$$Economic\ Damage_{t,i,j} = RYL_{t,i,j} * Price_{t,i,j} * Prod_{t,i,j} \qquad (1.4)$$

On the other hand, there are different methods and metrics for monetizing the health impacts of air pollution. Most of the existing work focuses on mortality costs, but there is an emerging literature that covers other indirect effects such as illness and productivity losses. The VSL is the monetary value of a relative change in mortality risk reduction. It is generally estimated using indirect methods (e.g. surveys or hedonic models linking wages to risks of premature death).

[9] The AOT40 indicator represents the accumulated ozone exposure over a threshold of 40 ppb, measured as (µg/m3) *hour (from 08:00 to 20:00)

[10] The calculations are developed using the AOT40 indicator, as cumulative indices would be more robust indicators for estimating yield losses (Avnery et al., 2011). However, this metric omits O_3 concentration below 40 ppbv which may have additional effects (Emberson et al., 2009).

Since there is a lack of empirical studies for directly estimating the VSL for all countries in the world, some procedures have been developed to transfer the results of existing studies to other regions, aiming to overcome this limitation. The "Unit Value Transfer Approach", which is based on adjusting the VSL to all countries according to GDP and GDP growth rates, takes as a reference the widely-accepted VSL of the OECD for 2005. Following this method, the VSL of a country c in the year t is defined as:

$$\mathrm{VSL}_{c,t} = \mathrm{VSL}_{\mathrm{OECD},2005} * \left(\frac{Y_{c,2005}}{Y_{\mathrm{OECD},2005}}\right)^{b} * (1 + \%\Delta Y)^{b} \qquad (1.5)$$

Where $\mathrm{VSL}_{c,t}$ is the VSL for country c in year t; $\mathrm{VSL}_{\mathrm{OECD},2005}$ is the base value; Y is the GDP per capita; b is the income elasticity[11] of the VSL and $\%\Delta Y$ is the income growth rate. Results for OECD countries present a consistent range of base values ranging from 1.8 to 4.5 M$(2005) (OECD 2012). These lower and upper bounds will be incorporated in sensitivity analysis, with the default value used taken to be the median of this range. Once the VSL is obtained for each region defined (and updated to $2015) the associated morbidity costs are included. According to Narain and Sall (2016), morbidity includes a wide range of effects covering direct market costs related to the health system (e.g. treatments or ambulances) and other indirect implications like disability or opportunity costs. Searl et al. (2016) gather some reference endpoints in order to create a core set of effects to be covered when estimating the cost of morbidity. However, there is not a well-accepted methodology to directly estimate these effects, so, following OECD's guidelines (OECD 2014), morbidity costs are considered as 10% of the mortality costs.

Annex III gives the estimated VSL for each region, including the additional 10% for morbidity. The regional units are adjusted every ten years from 2020 to 2050 to account for real income growth. In order to capture the level of uncertainty, an estimation range is included based on the literature lower and upper bounds. Having obtained the regional value for each time period, multiplying these values by the number of premature deaths reported by TM5-FASST gives the total monetarized health impacts for each region. Both co-benefits and mitigation costs have to be transformed to net present value (hereinafter NPV). This PhD Thesis uses a discount rate of 3%, with other discounting values considered for sensitivity analysis. Given that it is GDP based, there are clearly some ethical aspects to consider. One implication is that human life is more valued in developed countries than in developing ones. Although it may suffer from moral problems of this kind, it is a well-known and widely used methodology that enables users to undertake climate policy analysis to cover health costs in each region in a way that reflects the way such costs are covered within the region.

[11] The income elasticity generally used for the VSL ranges from 0.8 to 1.2. This study applies the value of 0.8 proposed by the OECD for all countries. However, there are some studies that suggest the income elasticity value should be modified based on the regional average income levels, which will be explored in further research (Masterman and Viscusi, 2018; Viscusi and Masterman, 2017)

Structure

The rest of the thesis is organized as follows. **Chapter 2** examines ozone (O_3) driven yield damage its effects on agricultural markets in a baseline scenario, i.e. with no climate policy set. Current O_3 concentration levels entail significant damage to crop yields around the world. The reaction of the precursors emitted (mostly methane and nitrogen oxides) with solar radiation raises O_3 levels to above the thresholds established. The chapter shows current and predicted (up to 2080) relative yield losses driven by O_3 exposure for different crops, and the associated economic damage, using temporally and regionally adjusted prices. The RYLs are also re-set into an integrated assessment model (GCAM) to estimate the projected dynamics of agricultural markets. The predicted decrease in emissions of O_3 precursors could reduce agricultural damage over time for most regions, with the exception of some countries such as India, where higher future O_3 concentrations have significant impacts on crop yields. Wheat and soybeans are the crops most sensitive to O_3 exposure, while effects on corn and rice are smaller all over the world. The economic impacts of O_3 driven losses for the time frame analyzed total $M5041-5987 for corn, 9780-18830 for soybeans, 6726-10536 for rice, and 10421-12461 for wheat at 2015 values. When O_3 effects are taken into consideration, the estimated decrease in O_3 levels and the subsequent improvement in yields can be expected to change regional agricultural markets. Therefore, global production levels of crops could change by up to 0.9% (soybeans) from 2020 to 2080, while economic damage could be as great as 3.84% (rice). However, zooming in to a regional level, changes could be as great as 6% in production levels (India, rice) and 1.67% in economic damage (India, wheat).

Chapter 3 then analyzes the potential effects in terms of reduction of emissions of CO_2 and air pollutants of eliminating fossil fuel subsidies (FFS) in the European Union, and recycling them to promote rooftop solar energy. The results show that this policy could displace coal from the energy mix and help to reduce emissions of CO_2 and air pollutants. However, the net benefits in terms of health-related emissions would depend on the type of energy used to replace coal. In particular eliminating FFS in the European Union by 2030 would help to reduce CO_2 emissions by 1.8% due to fuel-switching. If the revenues are recycled to promote solar energy, the CO_2 reduction could increase to 2.2%. In addition, the reduction in coal consumption due to the elimination of FFS could help to reduce emissions of other pollutants such as SO_2 (-3%). However, in the absence of additional policies, the health co-benefit would be negligible, first because the absolute changes are small, and second because the reduction of some pollutants would be offset by increases in emissions of carbon monoxide (CO) and organic carbon (OC), due to the expansion of bioenergy.

Next, setting aside the idea of the potential health co-benefits and drawbacks of mitigation, **Chapter 4** analyzes the extent to which health co-benefits could offset the mitigation cost of achieving the targets set in the Paris climate agreement (2°C and 1.5°C) under different scenarios in which the emission abatement efforts are shared between countries in accordance with three preset equity criteria. Although the co-benefits of addressing problems related to both climate change and air pollution are recognized, there is little evidence comparing the mitigation costs and economic benefits of air pollution reduction for alternative approaches to meeting greenhouse gas targets. The conclusion reached is that substantial health gains can be achieved by taking action to prevent climate change. Some countries, such as China and India, could justify stringent mitigation efforts just by factoring health co-benefits into the analysis. The results also suggest that the intention expressed in the Paris Agreement of pursuing efforts to limit temperature increase to 1.5°C could make economic sense in some scenarios and countries if health co-benefits are taken into account.

Chapter 5 also explores the health co-benefits of meeting the 2°C target, but under different technological pathways. The chapter shows that significant co-benefits can be found for a range of technological options, such as introducing a limitation on biomass, carbon capture and storage (CCS), and nuclear power. Cumulative premature deaths may be reduced by 17-23% up to 2050 compared to the baseline, depending on the scenarios. However, the ratio of health co-benefits to mitigation costs varies substantially, from 1.45 when a bioenergy limitation is set to 2.19 when all technologies are available. A breakdown by regions shows that some, such as India and China, obtain far greater co-benefits than others. These co-benefits are even greater in the mid-term (2030) than over the whole horizon.

Finally, **Chapter 6** gives some insights into potential future research lines and sets out conclusions.

Chapter 2

Future impacts of ozone driven damages on agricultural systems

Introduction

Tropospheric ozone (O_3) is the most hazardous pollutant for crop yields (Emberson et al., 2018). When the crop is exposed to high O_3 concentration levels, it penetrates through the stomata during plant gas exchange and, as a strong oxidant, it induces different harmful effects, such as visible foliar injuries (necrosis and chlorosis), reduced photosynthesis, gene alteration, and a reduction in yields (Avnery et al., 2011; Emberson et al., 2018). Even though there are some other climate variables that affect significantly to crop yield variations such as temperature, precipitation or carbon fertilization effect (CFE), exposure to O_3 has the largest effect ,within expected environmental changes (Shindell, 2016). Consequently, the decrease in crop yields would entail severe problems related with food security (Long et al., 2005; Mills et al., 2011).

The main driver for the formation of O_3 is the reaction of the emitted precursors with solar radiation. Literature has extensively analyzed the effect of both greenhouse gases (GHG) (methane (CH_4)) and non-GHG air pollutants such as nitrogen oxides (NOx), carbon monoxide (CO) and non-Methane-Volatile Organic Compounds (NMVOC) on O_3 formation (Burney and Ramanathan, 2014). Dentener et al. (2005) proof that the possible reduction of these pollutants coming from implemented climate policies would result in significant decrease of O_3 concentration levels. Furthermore, the transportation of those species entails significant inter-regional effects, what means that the emission of a certain precursor in a determined region would influence in the O_3 formation of another one (Fiore et al., 2009). There are also several studies concluding that the individual effect of each precursor is different. While O_3 would respond linearly to reductions in CO or NMVOC emissions (Fiore et al., 2009), the O_3 decrease would be larger with NOx reductions (Wu et al., 2009). In this context, it has been demonstrated that actions against NOx or CH_4 would be the most effective ones in order to reduce O_3 concentration levels (Shindell et al., 2019; West et al., 2007). Furthermore, the side reduction of precursors resulting from the implementation of long term climate objectives (RCP or temperature) would have demonstrated effect on projected O_3 concentration levels (Sicard et al., 2017).

Different studies have analyzed the O_3 driven current crop damages using exposure-response functions (hereinafter ERF) (Avnery et al., 2011; Ghosh et al., 2018; Van Dingenen et al., 2009). They show that soybeans and wheat are the most O_3 sensitive crops, as their global losses would range from 6% to 16% and from 4% to 15%, respectively. Rice and corn would be less affected, as their potential crop damages would account for 3-4% and 2.5-5.5%, respectively. Wang and Mauzerall, (2004) showed that some Asian regions (China, Japan and South Korea), would have significantly higher O_3 damages on crops. According to this study, in those regions in 1990, the yield losses range from 1% to 9% for wheat, corn and rice, while, for soybeans, the damages would represent between 23% and 27%. Those losses would increase for 2020, when wheat, corn and rice would lose 2-16% of the yield, and soybeans between 28% and 35%.

Moreover, some literature estimates future O_3 effects on crops. Van Dingenen et al. (2009) shows the potential crop losses for 2030, following the "current legislation" scenario (CLE)[12]. They apply the TM5-FASST air quality model and demonstrate that the present-day effects would deteriorate significantly, mostly for wheat and rice. The additional yield losses for these crops would account for 2-6% and 1-6%, respectively, due to the increase on future O_3 concentration levels. In this line, Chuwah et al. (2015) combined an integrated assessment model (IMAGE) with TM5-FASST, and they reported that crop losses would reach up to 20% in

[12] Details of the scenario can be found in Stohl et al., 2015

2050. In addition, by implementing stringent climate policies (RCP2.6), those yield losses would be significantly limited, as they would not exceed the 10% over the world.

Nevertheless, the aforementioned literature does not analyze future dynamics on agricultural markets. Projected reductions in yield productivity would modify the production of each commodity both globally and regionally. So, these changes in production levels would consequently affect the price of each crop. Moreover, there are many factors affecting the demand of each crop, which does not directly respond to productivity changes. The aim of this chapter is not only to estimate future O_3 driven RYLs and the subsequent economic impact, but to analyze the impacts on regional agricultural markets. For that purpose, an innovative approach has been applied that subsequently connects an integrated assessment model (GCAM) with an air quality tool (TM5-FASST) which has been explained in detail in the introduction. Furthermore, the application of this approach allows to calculate future economic damages by using temporal and spatially dynamic price estimations, giving a more accurate estimation of the damages than using the current prices, as has been done in the analyzed literature. In this study GCAM 4.4 is used with regional agricultural markets and food demand split into staple and non-staple categories[13], as the response of consumers to changes in prices and income are less elastic for staple crops than for non-staple crops. To meet global demand for agricultural products, farmers in different Agro-Ecological Zones (Monfreda et al 2007) of each region compete on prices for their share in the regional market, and subsequently, regional markets compete with each other for their share in the global market for agricultural commodities. Table 2.1 summarizes the methodology step by step, while Table 2.2 details the crop mapping developed. More information about the methods and models can be found in the *methodology* subsection.

Table 2.1: Synthesis of the developed methodology

Procedure	Description
1- GCAM baseline	GCAM baseline scenario (no policy scenario) is run in order to get the regional emissions O_3 precursor for short, medium and long terms.
2- O_3 damage coefficients	Those regional precursors are fed into TM5-FASST period by period, and we obtain the different O_3 concentration levels and, therefore, the current and future O_3 driven yield losses.
3-Economic impact impacts	The calculated agricultural losses are multiplied with the regional prices by period and commodity that we extract from GCAM.
4-Analysis of the damages on global and regional crop markets	Yield losses into are re-set into GCAM in order to see potential impacts on different crop markets

[13] Staple crops refer to grains, roots and tubers. All other crops and animal products are represented as non-staple. See Annex II for a full list of crop commodities used in GCAM.

Table 2.2: GCAM crop mapping

GCAM crop	Commodity	Category	Mapped crop
Root_Tuber	cassava	C4	maize
	others	C3	Avg (rice,wheat)
FiberCrop	cotton	C3	Avg (rice,wheat)
Corn	maize	C4	maize
Rice	rice	C3	rice
OtherGrain	sorghum	C4	maize
	others	C3	Avg (rice,wheat)
OilCrop	soybean	C3	soybean
SugarCrop	sugarcane	C4	maize
	sugarbeet	C3	Avg (rice,wheat)
Wheat	wheat	C3	wheat
MiscCrop	All MiscCrop	C3	Avg (rice,wheat,soybeans)
Pasture	All Pasture	C4	maize
biomass	All biomass	C4	maize
UnmanagedLand	All UnmanagedLand	C3	Avg (rice,wheat,soybeans)
FodderGrass	All FodderGrass	C4	maize
FodderHerb	All FodderHerb	C3	Avg (rice,wheat,soybeans)
PalmFruit	PalmFruit	C3	soybeans

Results

Air pollutant emissions and O_3 concentration levels

Figure 2.1 shows CH_4 and NOx emissions per region and period, as they are the most significant factors for O_3 formation (Shindell et al., 2019; West et al., 2007). Note that the results are presented for 32 GCAM regions. Annex I details the information about countries and regions.

Figure 2.1: O_3 main precursor emissions (CH_4 and NOx) per region and period (Tg)

In absolute terms, China, India, Russia and USA have the largest emissions. However, future CH_4 and NOx emission pathways have different trends. On the one hand, Figure 2.1 shows that emissions of CH_4, with no climate policy established, would increase in almost all of the regions. Nonetheless, NOx emissions would be flat or decrease all around the world. The reason is that GCAM implicitly incorporates some measures against air pollutants, based on planned emission control policies or future technological developments, which, despite the uncertainties, would better estimate future emissions (Smith et al., 2005). The emissions of other O_3 precursors such as CO or NMVOCs are summarized in Figure 2.2 and Figure 2.3.

Figure 2.2: CO emissions per period and region (Tg)

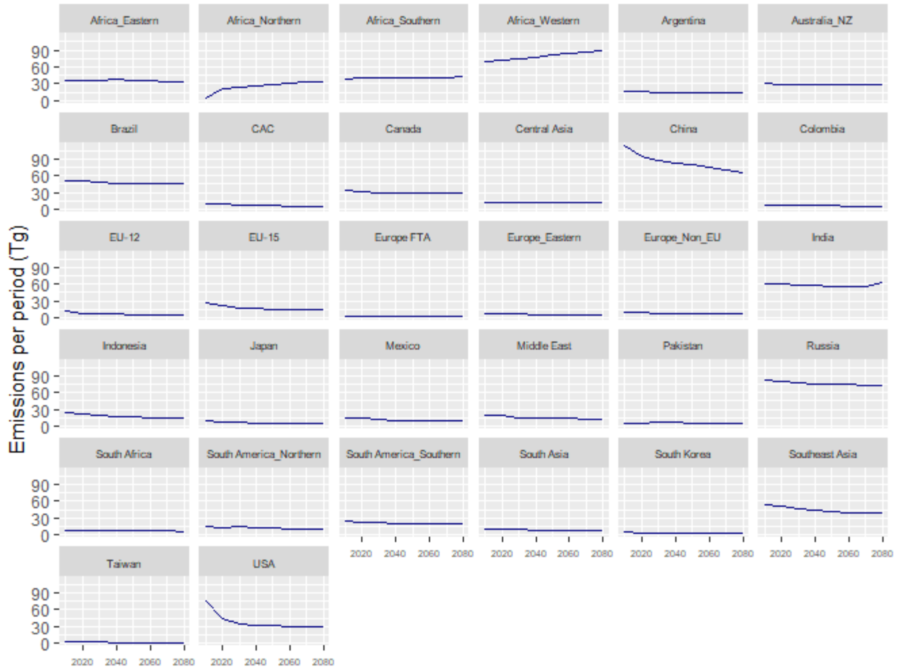
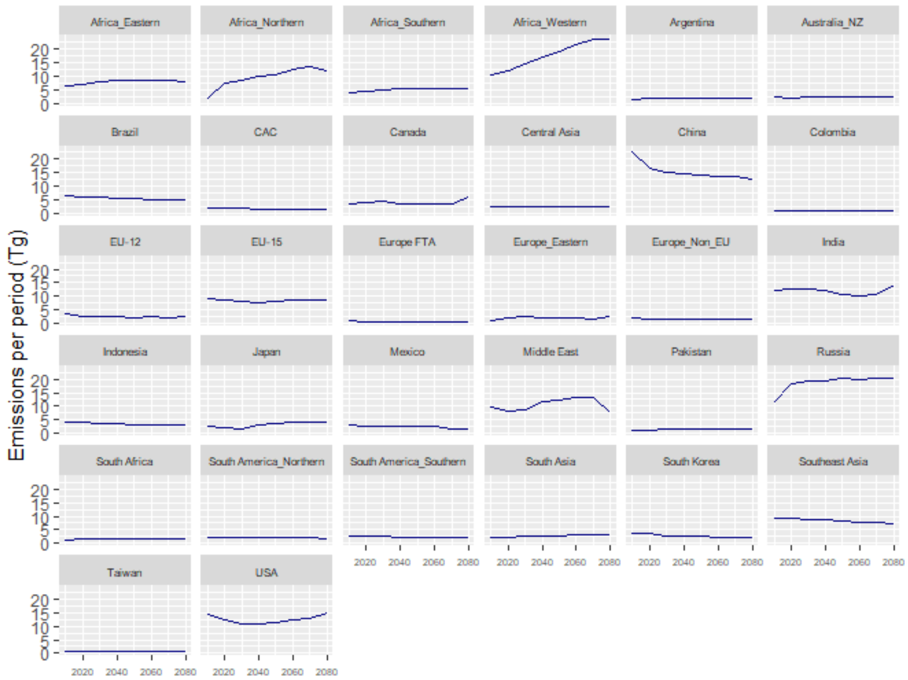
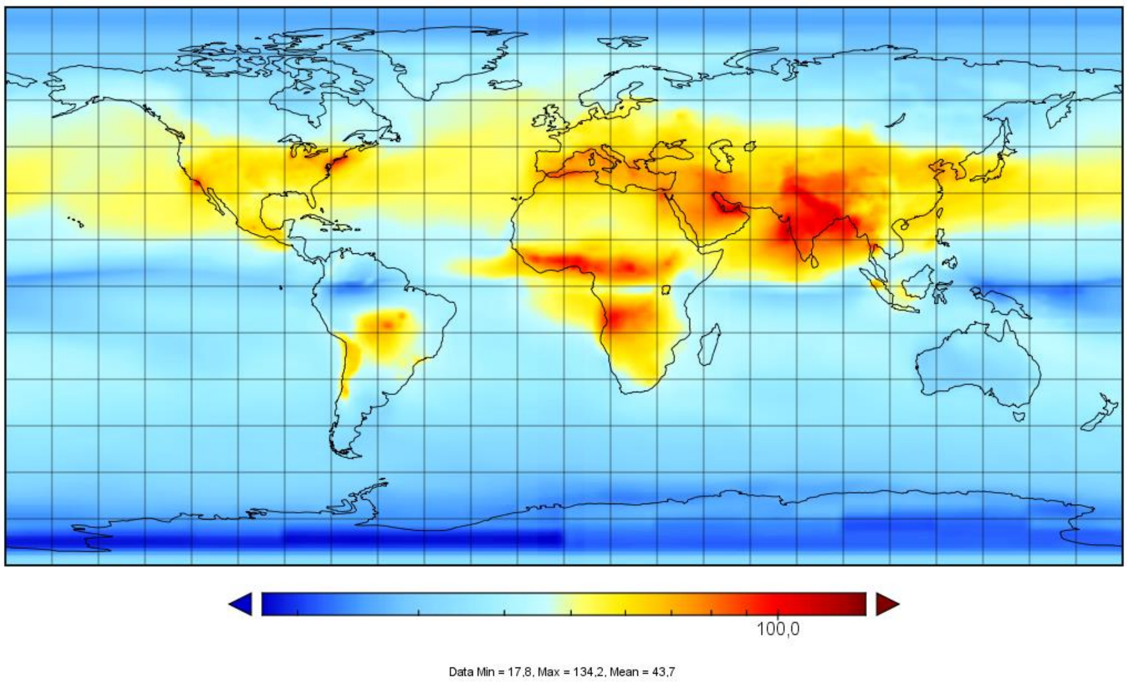


Figure 2.3: NMVOC emissions by period and region (Tg)



These emission pathways would result in different O_3 levels for every period. Figure 2.4 shows the gridded highest 3-monthly mean of daily maximum O3 level (M3M) for the medium term (2050), which is a representative indicator for O_3 exposure.

Figure 2.4: Maximal 3-monthly mean of daily maximum hourly ozone (log ppbv) in 2050

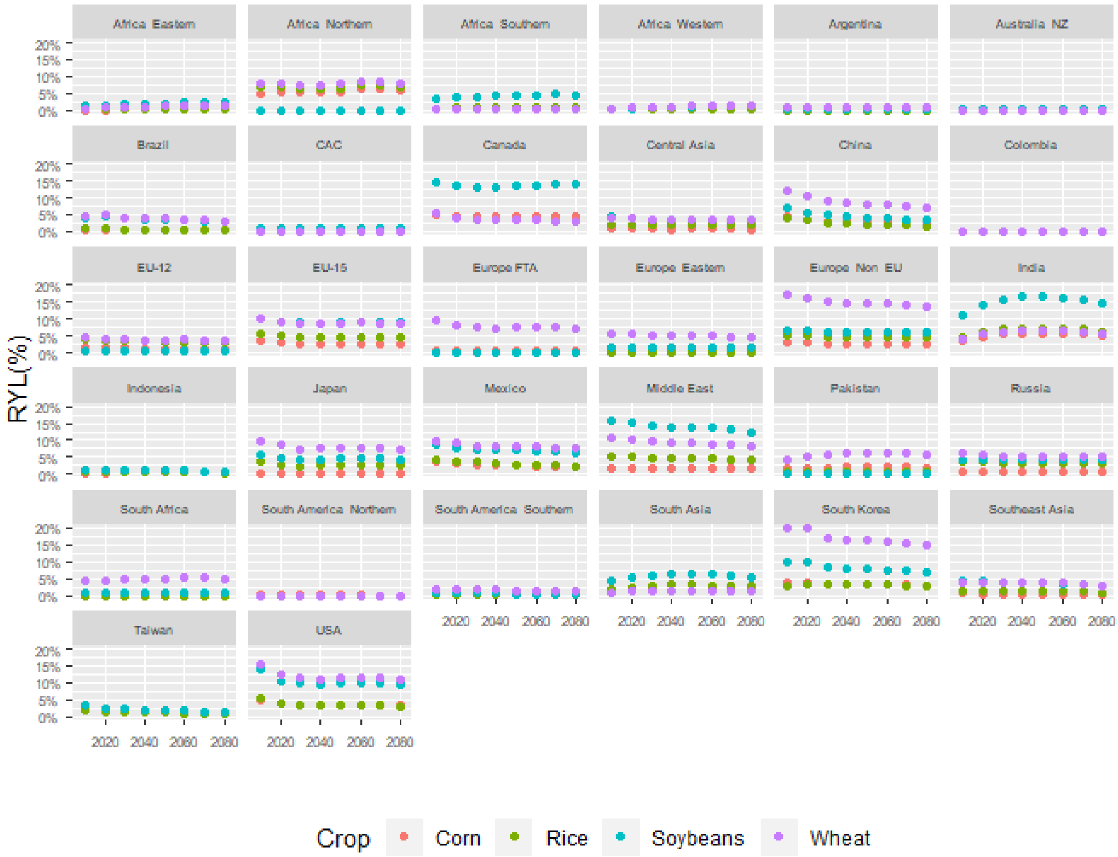


This figure shows that there are two main factors affecting O_3 distribution. First, the highest O_3 levels are formed around the equator. This happens because regions that are closer to the equator belt present the largest solar radiation level, as the reaction of O_3 precursors with solar radiation is essential for O_3 formation. On the other hand, there is a clear correlation between precursor emissions and O_3 concentration levels. Regions such as India, China or USA, which are the largest emitters of precursors (see Figure 2.1) have the highest M3M levels, resulting in larger agricultural damages. These M3M results are aligned with previous studies.(Brauer et al., 2016).

Relative yield losses (RYLs)

The resulting yield losses due to these O_3 concentration levels for the mentioned crops (corn, rice, wheat and soybeans) are summarized in Figure 2.5.

Figure 2.5: Relative Yield Lost (RYL) driven by O_3 exposure per period, crop and region (%)



This figure shows that, corn and rice crops are less sensitive to O_3 than wheat and soybeans, which is consistent with the aforementioned literature. The regions where corn present the largest yield losses during the analyzed time horizon (2020-2080) are Africa Northern (5-6%), India (4-6%), Canada (4-5%), USA (3-5%) and China (2.5-4.5%). Similar trends can be found for rice, as the most significant RYLs are located at Africa Northern (6-7.5%) and India (5-7.5%). Wheat damages are relatively larger, accounting for 15-19% in South Korea, 14-17% in Europe Non EU[14], 10-15% in USA, 7-12% in China, 8-10% in EU-15 and Middle East and 7.5-8.5% in Africa Northern. Likewise, soybeans suffer substantial RYLs in this time horizon, with largest effects in India (11-17%), Canada (13-14%), Middle East (12-15%) and USA (9-13%).

Regarding the timing, Figure 2.5 demonstrates that most of the regions have decreasing RYLs for each crop up to 2080 compared to current damages, due to the reduction of future O_3 concentration levels. However, some regions show larger RYLs over time, driven by significant increases of some precursors. For example, in India, future crop damages would increase with respect to current levels. In 2050, the relative increments (with respect to the base year) would range from 47% (soybeans) to 56% (rice). The main reason is the substantial increase in CH_4 emissions up to 2050 (see Figure 2.1), which more than double with respect to 2010 (127%). As the O_3 exposure metric is a key factor for the results (Lefohn et al., 2018), Table 2.3 includes a detailed description of the RYL per region, crop and period applying both AOT40 and Mi metrics.

[14] This region includes, Albania, Bosnia-Herzegovina, Croatia, Macedonia and Turkey

Table 2.3: RYL per period and region, using both AOT40 (first number) and Mi (second number) as ozone exposure metric

GCAM region	Crop	2010	2020	2030	2040	2050	2060	2070	2080
Africa_Eastern	MAIZE	0.1-0.4%	0.1-0.4%	0.1-0.4%	0.2-0.4%	0.2-0.5%	0.2-0.5%	0.2-0.5%	0.2-0.5%
Africa_Eastern	RICE	#N/A	0.3-0.2%	0.3-0.2%	0.4-0.3%	0.4-0.3%	0.4-0.3%	0.5-0.3%	0.5-0.3%
Africa_Eastern	SOY	1.3-2.8%	1.5-3.0%	1.8-3.3%	1.9-3.4%	2.1-3.5%	2.2-3.7%	2.3-3.8%	2.3-3.8%
Africa_Eastern	WHEAT	0.6-1.1%	0.8-1.2%	0.9-1.3%	1.0-1.4%	1.1-1.5%	1.3-1.5%	1.4-1.6%	1.3-1.5%
Africa_Northern	MAIZE	5.1-8.8%	5.3-9.1%	5.2-8.9%	5.2-9.0%	5.4-9.3%	6.2-10.6%	6.2-10.6%	5.7-9.9%
Africa_Northern	RICE	#N/A	6.7-3.7%	6.4-3.6%	6.3-3.6%	6.6-3.7%	7.5-4.3%	7.5-4.3%	6.9-3.9%
Africa_Northern	SOY	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
Africa_Northern	WHEAT	7.8-3.2%	7.8-3.3%	7.6-3.3%	7.6-3.3%	7.8-3.4%	8.3-3.7%	8.3-3.7%	7.9-3.5%
Africa_Southern	MAIZE	0.2-0.6%	0.2-0.7%	0.3-0.7%	0.3-0.7%	0.3-0.8%	0.4-0.8%	0.4-0.8%	0.4-0.8%
Africa_Southern	RICE	#N/A	0.6-0.3%	0.7-0.4%	0.7-0.4%	0.8-0.4%	0.8-0.4%	0.8-0.4%	0.8-0.4%
Africa_Southern	SOY	3.4-5.6%	3.8-5.9%	4.1-6.1%	4.3-6.2%	4.5-6.4%	4.6-6.4%	4.7-6.5%	4.6-6.4%
Africa_Southern	WHEAT	0.2-0.2%	0.3-0.3%	0.4-0.3%	0.4-0.3%	0.4-0.3%	0.5-0.3%	0.5-0.3%	0.4-0.3%
Africa_Western	MAIZE	0.2-0.7%	0.3-0.7%	0.3-0.8%	0.4-0.9%	0.5-1.1%	0.6-1.2%	0.6-1.2%	0.6-1.2%
Africa_Western	RICE	#N/A	0.2-0.2%	0.3-0.2%	0.3-0.2%	0.4-0.2%	0.4-0.3%	0.5-0.3%	0.5-0.3%
Africa_Western	SOY	0.2-2.6%	0.4-2.9%	0.6-3.3%	0.9-3.7%	1.1-4.1%	1.2-4.4%	1.3-4.6%	1.3-4.6%
Africa_Western	WHEAT	0.5-1.2%	0.7-1.3%	0.9-1.4%	1.1-1.5%	1.3-1.6%	1.5-1.7%	1.5-1.8%	1.5-1.7%
Argentina	MAIZE	0.1-1.5%	0.1-1.5%	0.1-1.3%	0.1-1.2%	0.1-1.2%	0.1-1.2%	0.1-1.2%	0.1-1.1%
Argentina	RICE	#N/A	0.0-0.2%	0.0-0.2%	0.0-0.2%	0.0-0.1%	0.0-0.1%	0.0-0.1%	0.0-0.1%
Argentina	SOY	0.3-6.5%	0.3-6.6%	0.3-6.0%	0.2-5.7%	0.2-5.7%	0.2-5.6%	0.2-5.4%	0.2-5.3%
Argentina	WHEAT	0.9-1.3%	0.9-1.3%	0.9-1.1%	0.8-1.1%	0.8-1.0%	0.7-1.0%	0.7-1.0%	0.6-0.9%
Australia_NZ	MAIZE	0.0-0.7%	0.0-0.6%	0.0-0.6%	0.0-0.7%	0.0-0.7%	0.0-0.7%	0.0-0.7%	0.0-0.7%
Australia_NZ	RICE	#N/A	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
Australia_NZ	SOY	0.1-4.1%	0.1-4.0%	0.2-4.1%	0.2-4.1%	0.2-4.2%	0.2-4.1%	0.2-4.1%	0.2-3.9%
Australia_NZ	WHEAT	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.1%	0.0-0.0%	0.0-0.0%	0.0-0.0%
Brazil	MAIZE	0.5-2.3%	0.5-2.4%	0.5-2.2%	0.5-2.2%	0.5-2.2%	0.5-2.1%	0.5-2.1%	0.4-2.0%
Brazil	RICE	#N/A	0.8-0.8%	0.6-0.7%	0.6-0.7%	0.6-0.7%	0.5-0.6%	0.5-0.6%	0.5-0.6%
Brazil	SOY	4.1-11.9%	4.4-12.1%	3.8-11.4%	3.5-11.0%	3.5-10.9%	3.3-10.7%	3.2-10.5%	2.9-10.2%
Brazil	WHEAT	4.6-3.3%	4.9-3.4%	4.2-3.0%	3.9-2.8%	3.8-2.7%	3.6-2.6%	3.4-2.5%	3.1-2.3%
Canada	MAIZE	4.9-8.0%	4.5-7.6%	4.4-7.5%	4.3-7.5%	4.5-7.7%	4.6-7.8%	4.6-7.9%	4.7-7.9%
Canada	SOY	14.3-17.3%	13.5-17.1%	13.2-17.2%	13.1-17.1%	13.4-17.4%	13.7-17.6%	13.8-17.7%	13.9-17.8%
Canada	WHEAT	5.7-4.3%	4.1-3.8%	3.5-3.5%	3.3-3.5%	3.3-3.5%	3.3-3.5%	3.2-3.5%	3.0-3.4%
CAC	MAIZE	0.3-0.8%	0.3-0.8%	0.3-0.8%	0.3-0.7%	0.2-0.7%	0.2-0.6%	0.2-0.6%	0.2-0.5%

CAC	RICE	#N/A	0.2-0.2%	0.1-0.2%	0.1-0.2%	0.1-0.2%	0.1-0.2%	0.1-0.2%	0.1-0.1%
CAC	SOY	1.0-4.9%	1.1-4.9%	1.1-4.9%	1.1-4.8%	1.1-4.8%	1.1-4.7%	1.1-4.7%	1.0-4.5%
CAC	WHEAT	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
Central Asia	MAIZE	0.8-1.7%	0.8-1.7%	0.7-1.7%	0.7-1.6%	0.7-1.7%	0.7-1.7%	0.7-1.7%	0.7-1.6%
Central Asia	RICE	#N/A	2.0-1.4%	1.9-1.3%	1.8-1.3%	1.9-1.3%	1.9-1.3%	1.9-1.3%	1.8-1.3%
Central Asia	SOY	4.3-13.0%	4.1-12.6%	3.7-12.2%	3.6-12.1%	3.7-12.2%	3.7-12.2%	3.7-12.2%	3.5-12.0%
Central Asia	WHEAT	4.0-2.5%	3.9-2.4%	3.6-2.2%	3.5-2.2%	3.6-2.2%	3.6-2.2%	3.5-2.2%	3.4-2.1%
China	MAIZE	4.5-7.1%	3.7-6.1%	3.2-5.4%	3.0-5.2%	2.9-5.0%	2.7-4.9%	2.6-4.7%	2.4-4.4%
China	RICE	#N/A	3.3-2.0%	2.7-1.7%	2.4-1.5%	2.2-1.4%	2.0-1.3%	1.9-1.2%	1.6-1.1%
China	SOY	6.9-12.2%	5.6-11.0%	4.8-10.2%	4.4-9.8%	4.2-9.6%	4.0-9.4%	3.7-9.2%	3.3-8.7%
China	WHEAT	12.3-4.6%	10.4-4.1%	9.1-3.8%	8.5-3.7%	8.2-3.7%	7.9-3.7%	7.5-3.6%	6.9-3.4%
Colombia	MAIZE	0.0-0.2%	0.0-0.2%	0.0-0.2%	0.0-0.2%	0.0-0.2%	0.0-0.1%	0.0-0.1%	0.0-0.1%
Colombia	RICE	#N/A	0.0-0.1%	0.0-0.1%	0.0-0.1%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
Colombia	SOY	0.0-0.1%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
Colombia	WHEAT	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
EU-12	MAIZE	1.6-3.3%	1.4-3.1%	1.3-3.0%	1.3-3.0%	1.3-3.0%	1.3-3.0%	1.3-3.0%	1.3-3.0%
EU-12	RICE	#N/A	3.8-2.2%	3.5-2.0%	3.4-2.0%	3.3-1.9%	3.3-1.9%	3.3-1.9%	3.2-1.9%
EU-12	SOY	0.6-1.3%	0.5-1.4%	0.5-1.5%	0.5-1.5%	0.5-1.5%	0.5-1.5%	0.5-1.6%	0.5-1.5%
EU-12	WHEAT	4.4-2.5%	4.0-2.4%	3.9-2.3%	3.8-2.3%	3.8-2.3%	3.8-2.3%	3.8-2.3%	3.7-2.3%
EU-15	MAIZE	3.4-6.2%	2.9-5.8%	2.7-5.6%	2.6-5.5%	2.6-5.6%	2.6-5.6%	2.6-5.6%	2.5-5.5%
EU-15	RICE	#N/A	4.9-2.7%	4.7-2.6%	4.6-2.6%	4.7-2.6%	4.8-2.7%	4.8-2.7%	4.7-2.7%
EU-15	SOY	10.3-14.8%	9.3-14.8%	8.9-14.9%	8.8-14.9%	8.9-15.1%	9.0-15.2%	9.0-15.3%	8.9-15.2%
EU-15	WHEAT	9.9-4.9%	9.2-4.8%	8.7-4.7%	8.6-4.8%	8.8-4.9%	8.9-4.9%	8.8-4.9%	8.6-4.8%
Europe_Eastern	MAIZE	1.2-2.7%	1.2-2.6%	1.2-2.5%	1.1-2.5%	1.1-2.5%	1.1-2.5%	1.1-2.5%	1.1-2.4%
Europe_Eastern	RICE	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
Europe_Eastern	SOY	1.8-5.4%	1.8-5.9%	1.8-6.2%	1.8-6.4%	1.8-6.6%	1.8-6.6%	1.8-6.7%	1.8-6.7%
Europe_Eastern	WHEAT	5.7-3.0%	5.4-2.8%	5.1-2.7%	4.9-2.6%	4.9-2.6%	4.9-2.6%	4.8-2.6%	4.7-2.5%
Europe_Non_EU	MAIZE	3.1-5.2%	3.0-5.0%	2.8-4.8%	2.7-4.7%	2.7-4.7%	2.7-4.6%	2.6-4.6%	2.5-4.5%
Europe_Non_EU	RICE	#N/A	4.9-2.6%	4.7-2.5%	4.6-2.5%	4.5-2.5%	4.5-2.5%	4.5-2.4%	4.4-2.4%
Europe_Non_EU	SOY	6.8-9.8%	6.5-10.0%	6.2-10.0%	6.1-10.1%	6.1-10.3%	6.0-10.3%	6.0-10.3%	5.9-10.2%
Europe_Non_EU	WHEAT	17.3-7.0%	16.4-6.6%	15.3-6.3%	14.8-6.1%	14.8-6.1%	14.7-6.1%	14.4-6.0%	13.8-5.8%
Europe FTA	MAIZE	0.7-1.5%	0.6-1.7%	0.5-1.7%	0.5-1.8%	0.5-1.9%	0.5-2.0%	0.5-2.0%	0.5-2.0%
Europe FTA	SOY	0.1-2.8%	0.1-4.1%	0.1-4.6%	0.1-5.0%	0.1-5.5%	0.1-5.8%	0.2-5.9%	0.1-5.9%
Europe FTA	WHEAT	9.5-5.0%	8.2-4.5%	7.6-4.3%	7.4-4.3%	7.5-4.3%	7.5-4.3%	7.4-4.3%	7.2-4.2%

India	MAIZE	3.8-7.2%	4.8-8.7%	5.4-9.7%	5.7-10.2%	5.8-10.4%	5.7-10.2%	5.5-9.9%	5.0-9.1%
India	RICE	#N/A	6.0-3.8%	6.9-4.4%	7.3-4.7%	7.3-4.7%	7.2-4.6%	6.9-4.4%	6.3-4.0%
India	SOY	11.3-18.9%	14.1-21.1%	15.8-22.4%	16.7-23.1%	16.7-23.1%	16.4-22.9%	15.8-22.4%	14.5-21.4%
India	WHEAT	4.2-2.5%	5.5-3.1%	6.2-3.5%	6.6-3.8%	6.6-3.8%	6.4-3.7%	6.2-3.6%	5.7-3.4%
Indonesia	MAIZE	0.3-2.1%	0.4-2.2%	0.4-2.3%	0.4-2.3%	0.5-2.3%	0.4-2.3%	0.4-2.2%	0.4-2.1%
Indonesia	RICE	#N/A	0.5-0.7%	0.5-0.8%	0.5-0.8%	0.5-0.8%	0.5-0.7%	0.4-0.7%	0.4-0.7%
Indonesia	SOY	1.2-5.4%	1.3-5.9%	1.3-6.0%	1.2-5.8%	1.1-5.7%	1.0-5.5%	0.9-5.2%	0.8-4.8%
Japan	MAIZE	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
Japan	RICE	#N/A	2.9-1.6%	2.4-1.5%	2.7-1.7%	2.8-1.8%	2.8-1.9%	2.8-1.9%	2.7-1.8%
Japan	SOY	5.8-11.5%	4.8-11.4%	4.1-11.3%	4.4-11.9%	4.5-12.2%	4.6-12.4%	4.6-12.5%	4.4-12.3%
Japan	WHEAT	9.8-4.2%	8.5-4.1%	7.3-4.0%	7.6-4.4%	7.7-4.5%	7.8-4.6%	7.6-4.7%	7.3-4.6%
Mexico	MAIZE	3.5-7.0%	3.2-6.5%	2.9-6.1%	2.6-5.8%	2.5-5.6%	2.4-5.5%	2.3-5.4%	2.1-5.2%
Mexico	RICE	#N/A	3.9-2.5%	3.5-2.3%	3.1-2.1%	2.9-2.0%	2.7-1.9%	2.6-1.9%	2.4-1.8%
Mexico	SOY	8.6-16.7%	7.8-16.1%	7.3-15.7%	7.0-15.4%	7.0-15.3%	6.8-15.2%	6.7-15.0%	6.3-14.7%
Mexico	WHEAT	9.9-6.1%	9.1-5.7%	8.4-5.4%	8.2-5.3%	8.2-5.2%	8.1-5.2%	7.9-5.1%	7.5-5.0%
Middle East	MAIZE	1.8-3.4%	1.8-3.3%	1.7-3.2%	1.6-3.1%	1.6-3.1%	1.6-3.1%	1.6-3.1%	1.5-2.9%
Middle East	RICE	#N/A	5.2-3.0%	4.8-2.8%	4.6-2.7%	4.6-2.7%	4.5-2.6%	4.4-2.6%	4.1-2.4%
Middle East	SOY	15.6-21.5%	15.2-21.2%	14.2-20.6%	13.8-20.3%	13.7-20.3%	13.5-20.2%	13.2-20.0%	12.3-19.3%
Middle East	WHEAT	10.7-4.7%	10.3-4.5%	9.5-4.2%	9.2-4.1%	9.0-4.0%	8.9-4.0%	8.7-3.9%	8.1-3.6%
Pakistan	MAIZE	1.7-3.1%	1.8-3.4%	1.9-3.5%	2.0-3.6%	2.0-3.7%	2.0-3.7%	1.9-3.6%	1.8-3.4%
Pakistan	RICE	#N/A	0.7-0.5%	0.8-0.6%	0.9-0.7%	0.9-0.7%	0.9-0.7%	0.8-0.6%	0.7-0.6%
Pakistan	SOY	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
Pakistan	WHEAT	4.4-2.5%	5.2-2.9%	5.7-3.1%	6.0-3.2%	6.1-3.3%	6.1-3.3%	6.0-3.2%	5.7-3.1%
Russia	MAIZE	0.6-1.4%	0.6-1.4%	0.6-1.4%	0.5-1.5%	0.6-1.5%	0.6-1.5%	0.6-1.5%	0.5-1.5%
Russia	RICE	#N/A	3.5-2.2%	3.3-2.1%	3.2-2.1%	3.3-2.1%	3.3-2.1%	3.3-2.1%	3.2-2.0%
Russia	SOY	4.2-8.4%	4.2-8.8%	4.0-9.0%	4.0-9.1%	4.1-9.3%	4.1-9.4%	4.1-9.4%	4.0-9.3%
Russia	WHEAT	6.1-3.3%	5.9-3.2%	5.5-3.1%	5.3-3.0%	5.4-3.0%	5.3-3.0%	5.3-3.0%	5.0-2.9%
South Africa	MAIZE	0.8-2.5%	0.9-2.6%	0.9-2.7%	1.0-2.8%	1.0-2.9%	1.0-2.9%	1.0-2.9%	1.0-2.8%
South Africa	RICE	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
South Africa	SOY	0.6-6.4%	0.7-6.7%	0.7-6.8%	0.8-6.9%	0.8-7.1%	0.8-7.1%	0.8-7.1%	0.8-7.0%
South Africa	WHEAT	4.1-3.1%	4.4-3.3%	4.7-3.4%	4.8-3.4%	5.0-3.5%	5.1-3.5%	5.1-3.5%	4.9-3.4%
South America_Northern	MAIZE	0.0-0.2%	0.0-0.2%	0.0-0.2%	0.0-0.2%	0.0-0.2%	0.0-0.1%	0.0-0.1%	0.0-0.1%
South America_Northern	RICE	#N/A	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
South America_Northern	SOY	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%

South America_Northern	WHEAT	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%	0.0-0.0%
South America_Southern	MAIZE	0.1-0.6%	0.1-0.6%	0.1-0.5%	0.1-0.5%	0.1-0.5%	0.1-0.4%	0.1-0.4%	0.1-0.4%
South America_Southern	RICE	#N/A	0.0-0.1%	0.0-0.1%	0.0-0.1%	0.0-0.1%	0.0-0.1%	0.0-0.1%	0.0-0.1%
South America_Southern	SOY	0.8-3.1%	0.8-3.0%	0.7-2.7%	0.6-2.5%	0.5-2.4%	0.4-2.3%	0.4-2.2%	0.3-2.0%
South America_Southern	WHEAT	2.0-1.6%	1.9-1.6%	1.8-1.5%	1.6-1.4%	1.5-1.3%	1.3-1.2%	1.3-1.1%	1.1-1.1%
South Asia	MAIZE	1.0-1.9%	1.1-2.1%	1.2-2.2%	1.2-2.2%	1.2-2.2%	1.2-2.2%	1.2-2.2%	1.1-2.1%
South Asia	RICE	#N/A	2.5-1.9%	2.9-2.2%	3.0-2.3%	3.0-2.3%	3.0-2.3%	2.9-2.2%	2.6-2.0%
South Asia	SOY	4.1-8.4%	5.2-9.4%	5.9-10.1%	6.2-10.4%	6.3-10.4%	6.2-10.3%	5.9-10.1%	5.4-9.6%
South Asia	WHEAT	0.9-0.5%	1.1-0.6%	1.2-0.6%	1.3-0.7%	1.3-0.7%	1.3-0.7%	1.3-0.7%	1.2-0.6%
South Korea	MAIZE	4.0-5.3%	4.0-6.6%	3.5-6.1%	3.4-6.1%	3.3-6.2%	3.2-6.1%	3.1-6.0%	3.0-5.8%
South Korea	RICE	#N/A	3.5-1.7%	3.1-1.6%	3.1-1.7%	3.1-1.8%	3.1-1.8%	3.0-1.8%	2.8-1.7%
South Korea	SOY	9.9-14.7%	9.6-16.2%	8.1-15.4%	7.9-15.4%	7.8-15.4%	7.5-15.3%	7.3-15.1%	6.8-14.8%
South Korea	WHEAT	19.8-8.0%	19.7-8.5%	16.9-7.5%	16.6-7.3%	16.4-7.3%	16.0-7.2%	15.5-7.0%	14.7-6.7%
Southeast Asia	MAIZE	0.6-3.3%	0.5-3.1%	0.5-2.9%	0.5-2.7%	0.4-2.5%	0.4-2.3%	0.4-2.1%	0.3-1.8%
Southeast Asia	RICE	#N/A	1.4-1.4%	1.3-1.4%	1.3-1.3%	1.3-1.2%	1.2-1.2%	1.1-1.1%	1.0-0.9%
Southeast Asia	SOY	4.4-11.7%	4.2-11.4%	4.0-11.1%	3.9-10.6%	3.8-10.2%	3.5-9.7%	3.3-9.3%	2.9-8.5%
Southeast Asia	WHEAT	3.7-3.1%	4.0-3.4%	4.0-3.6%	4.0-3.7%	3.8-3.6%	3.6-3.4%	3.4-3.3%	3.0-2.8%
Taiwan	MAIZE	1.6-2.8%	1.5-3.0%	1.4-3.0%	1.4-3.1%	1.4-3.2%	1.3-3.0%	1.2-2.9%	1.0-2.7%
Taiwan	RICE	#N/A	1.4-0.9%	1.2-0.8%	1.3-0.9%	1.2-0.9%	1.1-0.8%	1.0-0.7%	0.8-0.7%
Taiwan	SOY	3.6-8.5%	2.6-9.4%	2.1-9.6%	2.1-9.9%	2.0-10.0%	1.8-9.8%	1.5-9.6%	1.3-9.3%
USA	MAIZE	4.9-9.0%	3.8-7.6%	3.5-7.3%	3.5-7.2%	3.5-7.3%	3.6-7.4%	3.5-7.4%	3.4-7.2%
USA	RICE	#N/A	3.9-2.6%	3.4-2.4%	3.3-2.3%	3.3-2.3%	3.3-2.3%	3.3-2.3%	3.1-2.3%
USA	SOY	13.8-20.4%	10.7-18.5%	9.8-18.0%	9.6-17.9%	9.7-18.0%	9.8-18.0%	9.8-18.0%	9.5-17.8%
USA	WHEAT	15.3-7.0%	12.3-6.1%	11.4-5.9%	11.2-5.8%	11.3-5.9%	11.4-5.9%	11.3-5.9%	10.8-5.7%

Economic Damages

The estimated yield losses have an associated economic impact, as presented in Figure 2.6[15].

[15] In GCAM, soybeans are included the OilCrop category. Economic damages have therefore been estimated for the whole category. See Annex II for a full list of commodities included in this category.

Figure 2.6: Economic damage driven by O_3 exposure per region, period and crop (M$(2015))

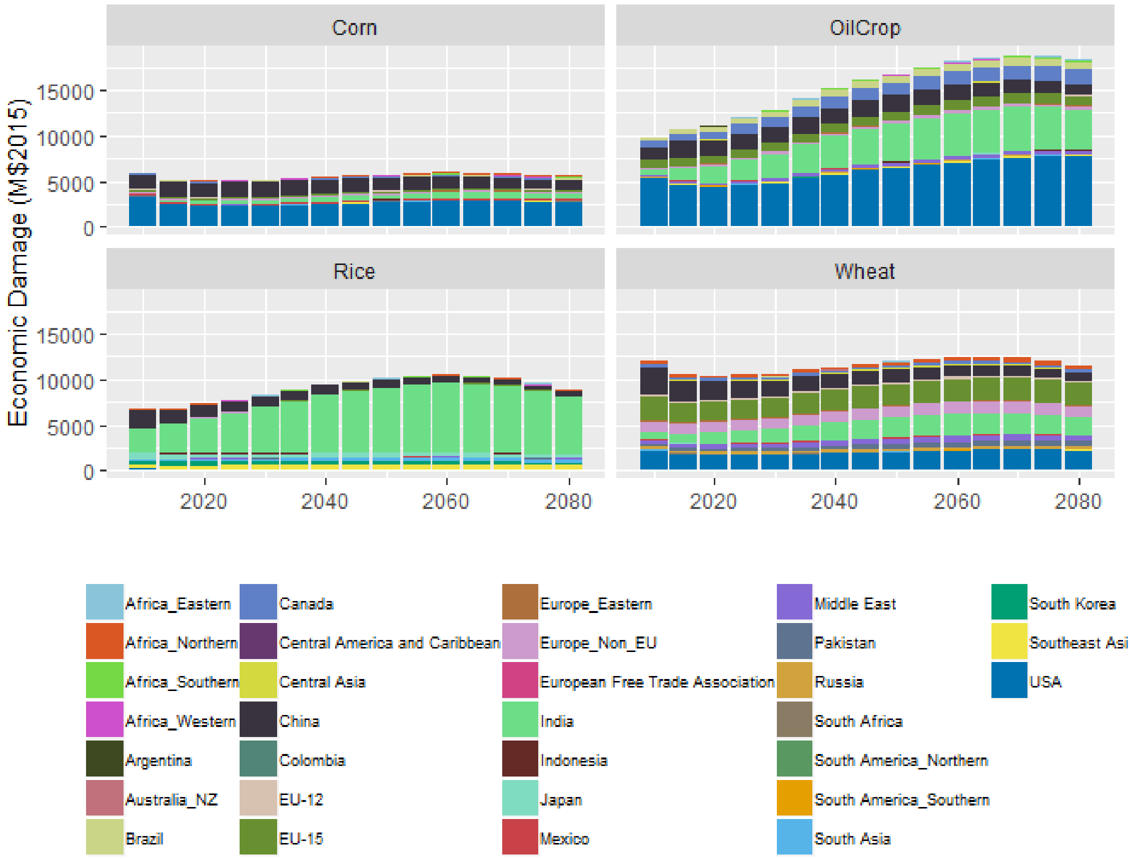


Figure 2.6 shows that corn driven economic losses decrease in the short term, and then they remain relatively unaltered, ranging from 5000 to 6000 M$(2015). USA, which is the largest corn producer (33-38%), suffers the majority of damages, accounting for 44-55% of global corn damages, depending on the period. China, which produces between 18% and 23% of the corn, also puts up with a significant part of the damages (18-31%). Oilcrops, the category that includes soybeans, suffer a large increase in economic damages mostly driven by global production volume, doubling between 2010 and 2050. So, while the economic damages account for 9780 M$(2015) in 2010, they increase up to 18341 M$(2015) in 2080. In regional terms, USA suffers the largest damage (38-54%) being the largest producer (18-22%), followed up by India, which suffered only the 7% of the economic damage in 2010, but increasing significantly to 24% of global oilcrop damages by 2080. Economic damages of rice crops also increase during most of the 21th century (from 6788 M$(2015) in 2010 to 10132 M$(2015) in 2070), whereas global production changes during the analyzed period are smaller than 10%. China, India and South-East Asia are the larger producers; however, economic damages in South-East Asia are limited due to relatively low O_3 concentration levels. Therefore, India (in the long term) and China bear most of the damages. Concretely, these regions suffer between 37-72% and 5-30% of the total rice damages, respectively. Finally, the figure shows that economic damages of wheat follow a relatively unaltered pattern, as they range from 10421 M$(2015) to 12461 M$(2015) during the analyzed time period. The regional allocation of the damages varies significantly depending on the time horizon, but the cost is principally born by four of the larger producers which are China, EU-15, India and USA. In the short term (2020) China suffers the largest damages (19-24%), followed by EU-15 (20-21%), USA (16-18%) and India (7-12%). However, in the long term (2080) damages in China (7% of the total) drop drastically and increase in India. Therefore, in 2080, the

largest impacts are located in EU-15, USA and India, representing the 21%, 19% and 17% of the total wheat damages, respectively.

Impacts on agricultural markets

As explained, to re-set the yield losses into GCAM allows to analyze which would be the effects of including future O_3 driven crop damages in the agricultural systems. For that purpose, the default GCAM baseline scenario is compared with a scenario where the estimated O_3 damages are incorporated (baseline+O_3). Then, differences in production levels and the subsequent changes in economic impact are examined, both globally and regionally.

In terms of production, the implications of considering the O_3 effects are analyzed, by identifying three different effects. First, it is examined which would be the changes in production per region and commodity driven by changes on yield productivities (*O_3 impact*). However, the demand of each crop would also affect to total production, since it would not directly respond to changes in productivity, so there would also be a *substitution effect*. Finally, the *consumption effect* is also isolated. While globally the consumption of each commodity will be equal to the production, there are significant regional divergences due to the market dynamics.

For the analysis of the O_3 implications for economic damages, the total results are decomposed in three different effects. Initially, economic damages depend on future changes in O_3 concentration levels and how they alter total crop production (*O_3 impact*). Such impacts on crop productivity translate to changes in crop prices, affecting total economic damage (*Price effect*). Finally, regional crop price changes modify regional distribution of crop production. So, there is a *substitution effect*, which directly affects production levels and, therefore, economic damages per region.

Figure 2.7: O_3 implications for production levels (A) and for economic damages (B) per period, region and commodity

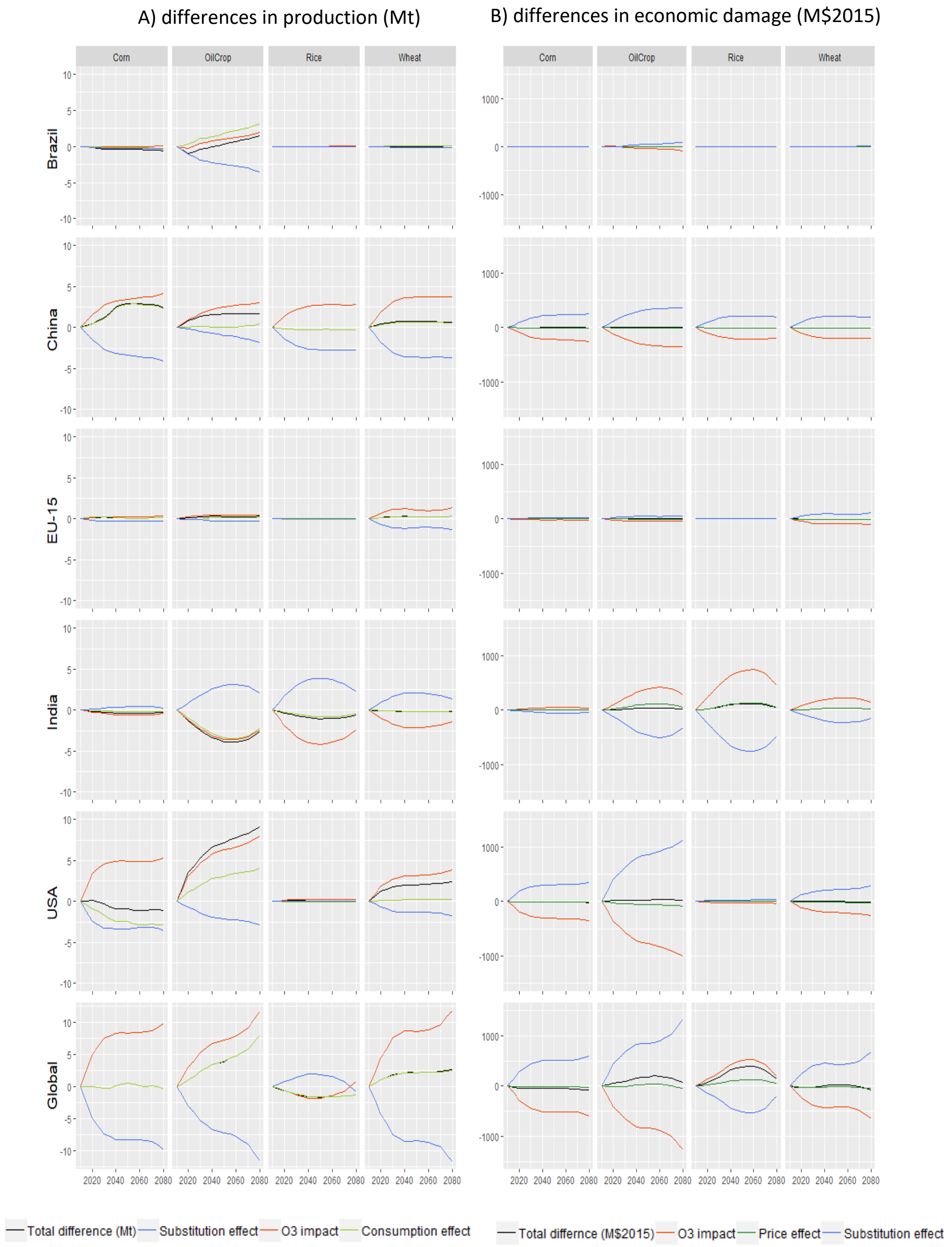
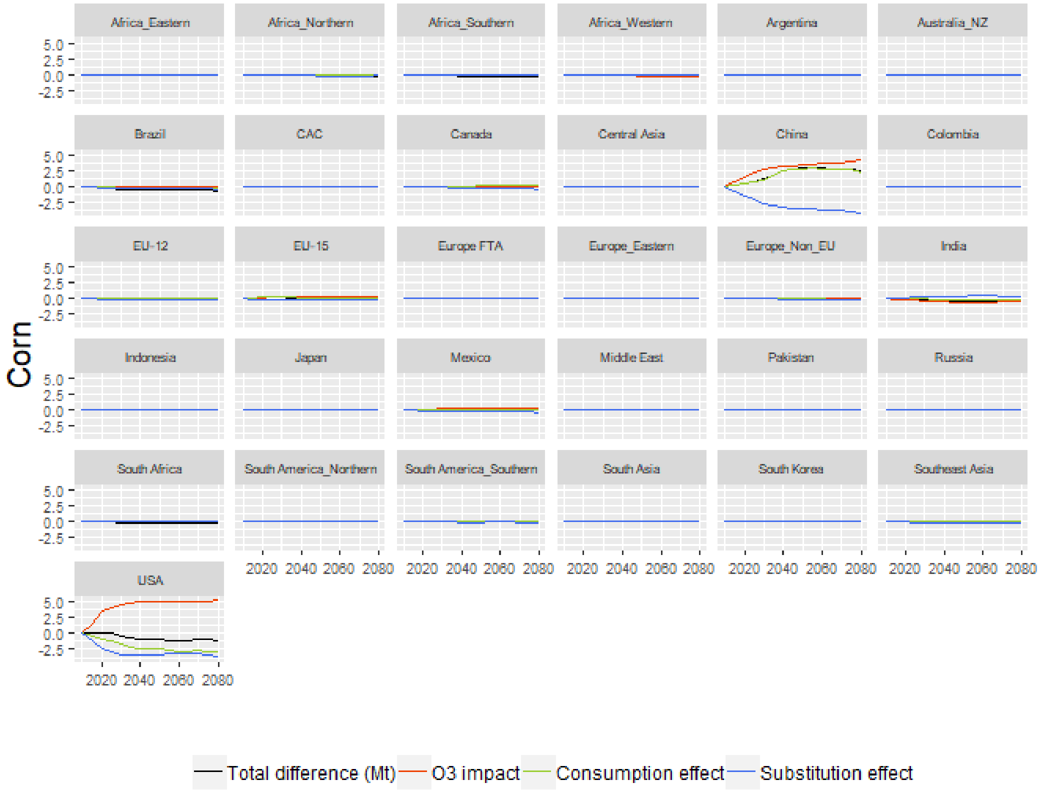
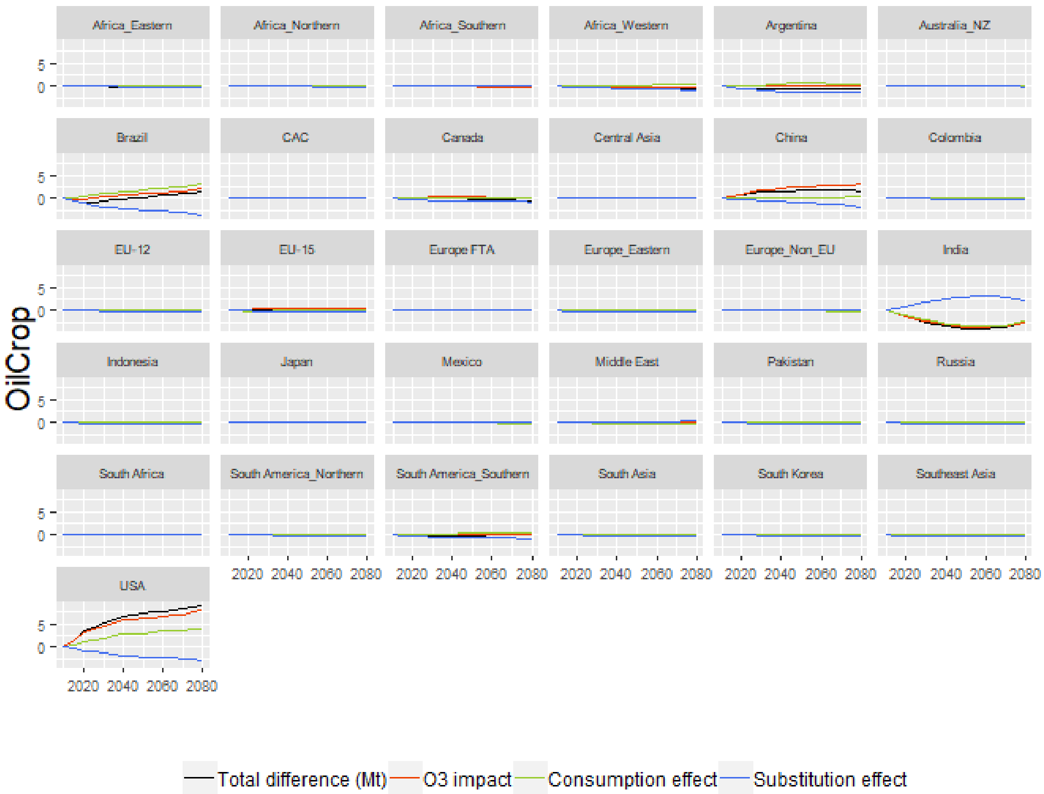


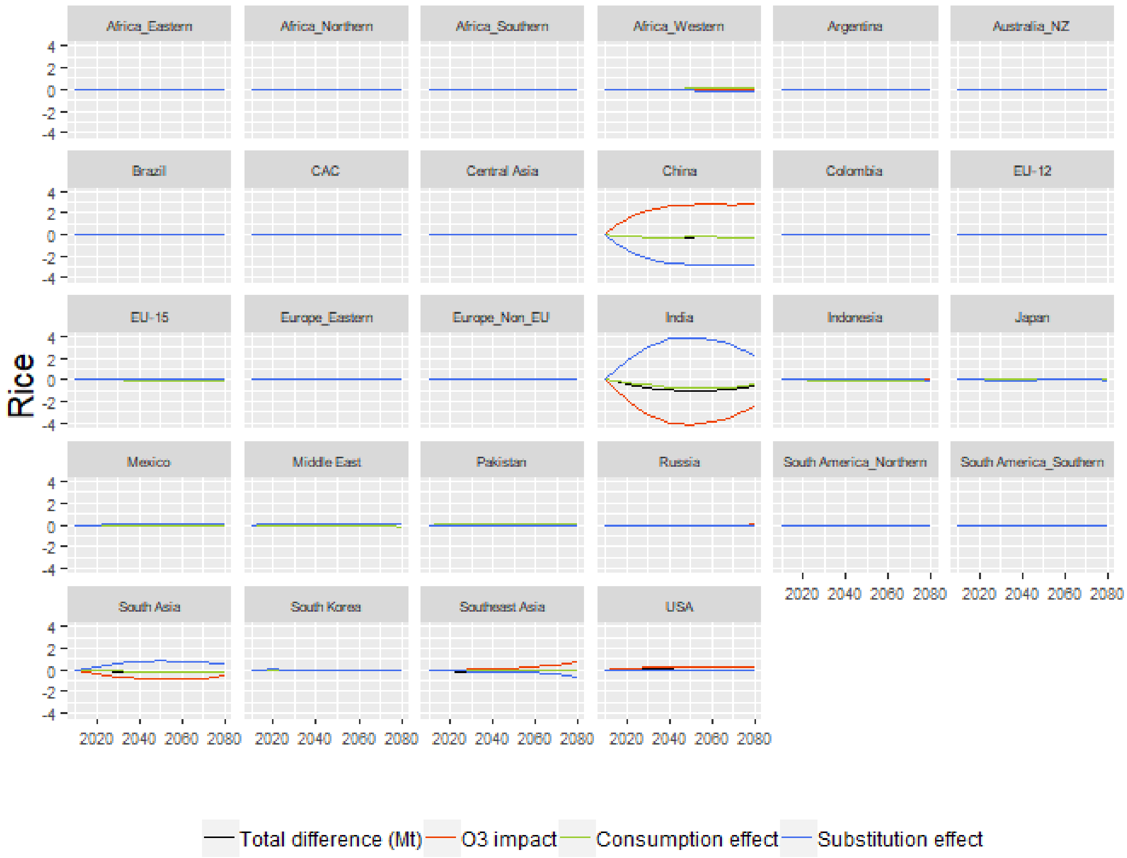
Figure 2.7 shows that both production and economic impacts significantly vary per region, period and commodity when considering O_3 driven yield losses. Corn production, at a global level, does not suffer large changes. Even though there is a considerable increase on yield productivity driven by smaller O_3 concentration levels (mostly in USA and China), this does not translate to a large increase in demand. This implies a reduction on corn land requirement, which may produce positive side effects. However, the economic damages would be reduced by

83 M$(2015) up to 2080, due to the reduction in O_3 concentration levels. Taking into account that economic damages range from 5000 to 6000 M$(2015), this reduction represents between 1.33% and 1.66% of total economic damage. The figure also shows that some regions such as USA would reduce their corn consumption, which would be compensated with an increase in some other countries (f.e. China). On the contrary, oilcrop production increases by almost 8 Mt up to 2080, due to the positive yield changes in some regions such as Brazil, China and USA that outweigh the yield decreases in countries like India. However, economic damages of oilcrops increase up to 203 M$(2015) (around 1.16%) because, even though there is a reduction in O_3 levels, there is an increase in demand (*substitution effect*) that compensates that reduction. Oilcrops are not limited to food demand as they are often used for energy purposes, for which the price elasticity is significantly higher, explaining the unique effect we observe for oilcrops. O_3 effects on rice production are largely explained by the results for India. This region is one of the main producers of rice, and it presents a large increment in O_3 concentration levels driven by a positive trend of CH_4 emissions (see Figure 2.1). Consequently, there is a significant decrease in yield productivity, but as the demand does not respond in the same way, the decrease in total rice production is softened, accounting for 1-1.7 Mt during the analyzed period, with an increase in the amount of land required for rice production. Global production of wheat increases from 1.03 (2020) to 2.55 (2080) megatons, driven primarily by positive increments in yield productivity for some of the larger wheat producers such as EU-15, China and USA. In India, wheat productivity diminishes during the analyzed time horizon but it does not translate to a modification in the demand so the production remains relatively unaltered. Variations in economic damages show a variable trend: the decrease in the short term between -33 and -14 M$2015 (-0.32% and -0.13%) is followed by an increment between 2040 and 2065 of 3-29 M$2015(up to 0.23%). In the long term, the economic damages decrease 82 M$2015 (-0.71%) by 2080. The following figures provide a regional description of the changes in both production and economic damages.

Figure 2.8: O_3 implications in production levels per region, crop, period and effect (Mt)






Rice
Africa_Eastern
Africa_Northern
Africa_Southern
Africa_Western
Argentina
Australia_NZ
Brazil
CAC
Central Asia
China
Colombia
EU-12
EU-15
Europe_Eastern
Europe_Non_EU
India
Indonesia
Japan
Mexico
Middle East
Pakistan
Russia
South America_Northern
South America_Southern
South Asia
South Korea
Southeast Asia
USA
4
2
0
-2
-4
2020 2040 2060 2080
Total difference (Mt)
O3 impact
Consumption effect
Substitution effect

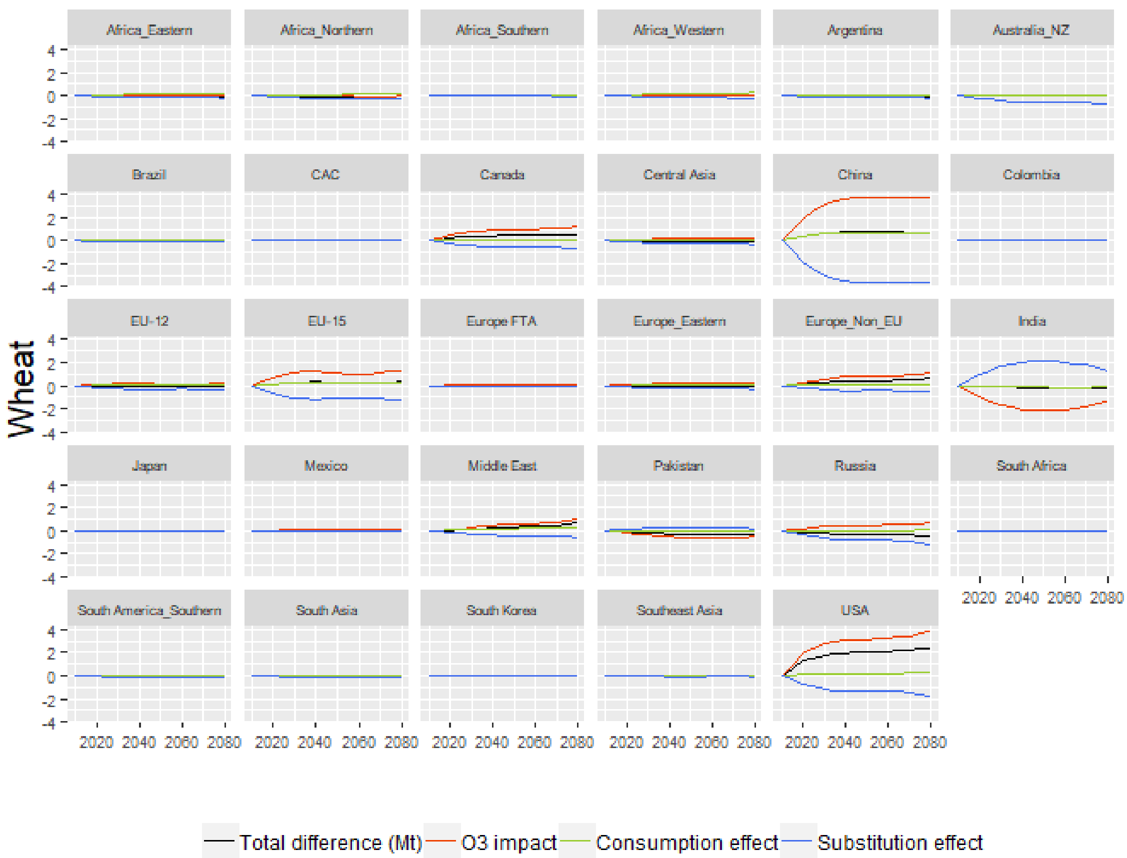
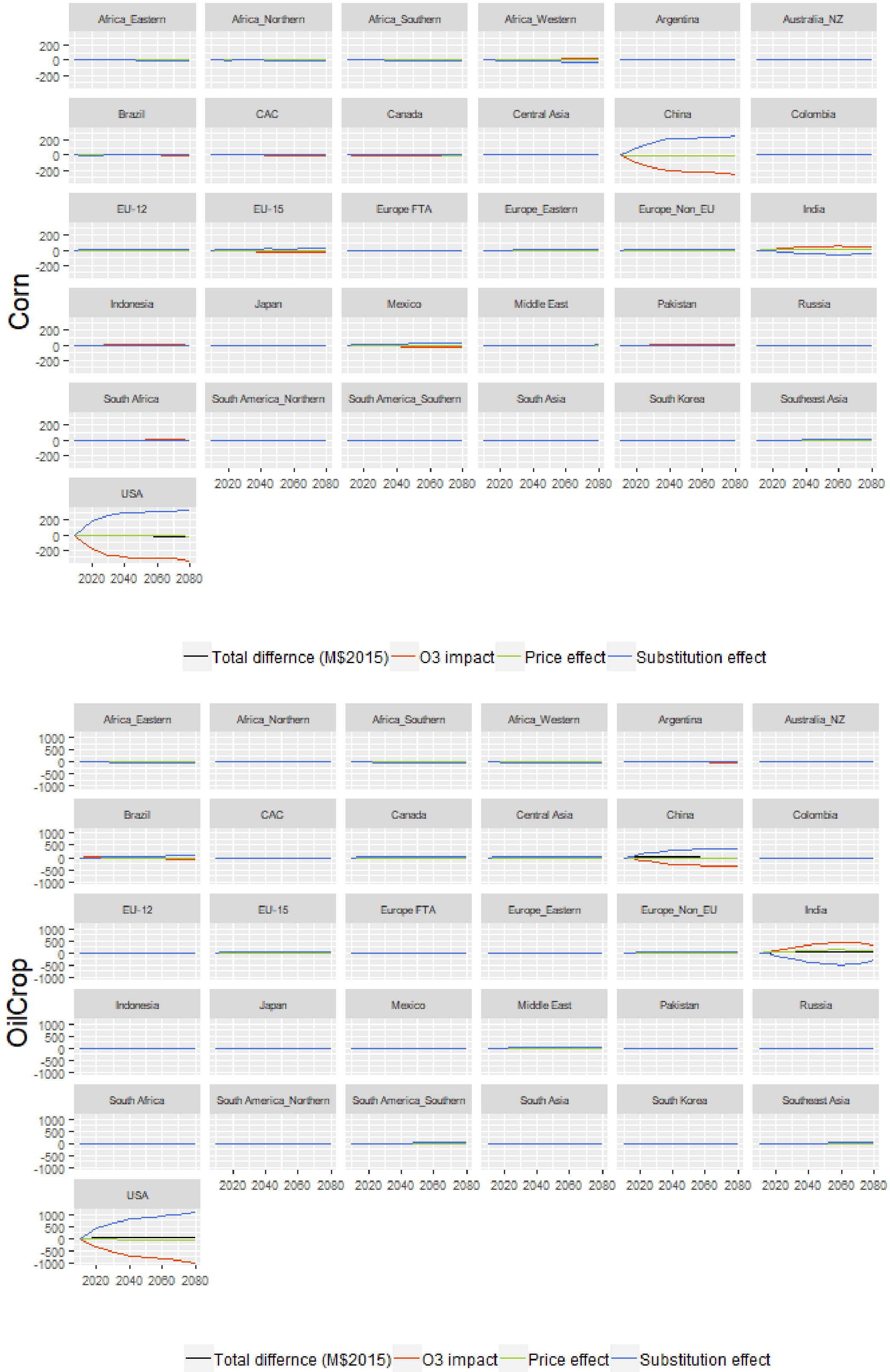
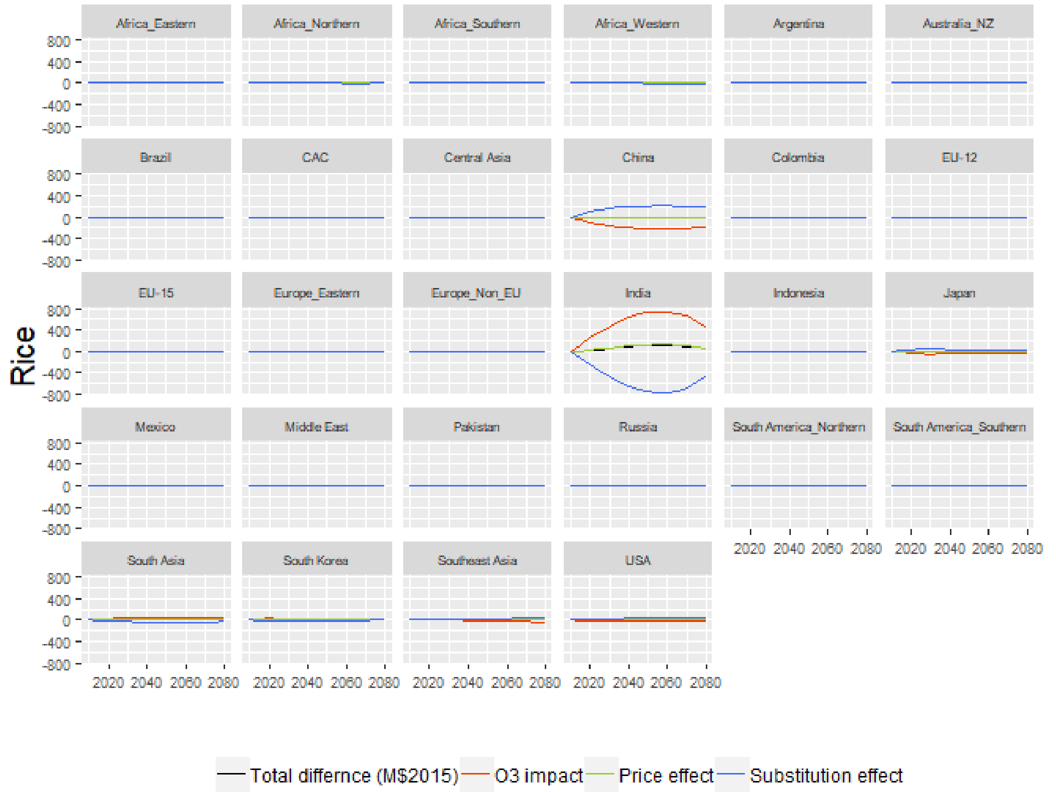
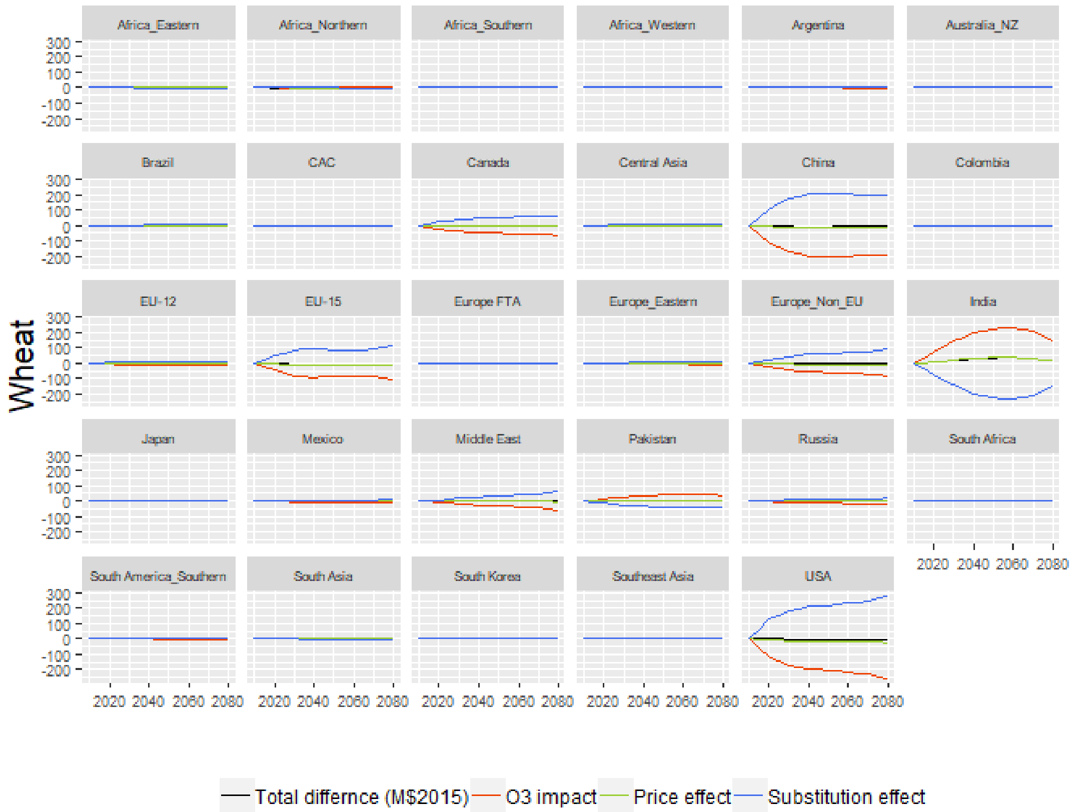

Wheat
Africa_Eastern
Africa_Northern
Africa_Southern
Africa_Western
Argentina
Australia_NZ
Brazil
CAC
Canada
Central Asia
China
Colombia
EU-12
EU-15
Europe FTA
Europe_Eastern
Europe_Non_EU
India
Japan
Mexico
Middle East
Pakistan
Russia
South Africa
South America_Southern
South Asia
South Korea
Southeast Asia
USA
4
2
0
-2
-4
2020 2040 2060 2080
Total difference (Mt)
O3 impact
Consumption effect
Substitution effect

Figure 2.9: O_3 implications in economic damages per region, crop, period and effect (M$2015)




Rice
Africa_Eastern
Africa_Northern
Africa_Southern
Africa_Western
Argentina
Australia_NZ
Brazil
CAC
Central Asia
China
Colombia
EU-12
EU-15
Europe_Eastern
Europe_Non_EU
India
Indonesia
Japan
Mexico
Middle East
Pakistan
Russia
South America_Northern
South America_Southern
South Asia
South Korea
Southeast Asia
USA
800
400
0
-400
-800
2020 2040 2060 2080
Total differnce (M$2015)
O3 impact
Price effect
Substitution effect


Wheat
Africa_Eastern
Africa_Northern
Africa_Southern
Africa_Western
Argentina
Australia_NZ
Brazil
CAC
Canada
Central Asia
China
Colombia
EU-12
EU-15
Europe FTA
Europe_Eastern
Europe_Non_EU
India
Japan
Mexico
Middle East
Pakistan
Russia
South Africa
South America_Southern
South Asia
South Korea
Southeast Asia
USA
300
200
100
0
-100
-200
2020 2040 2060 2080
Total differnce (M$2015)
O3 impact
Price effect
Substitution effect

Discussion

The obtained results are in line with the aforementioned literature (Avnery et al., 2011; Van Dingenen et al., 2009), but there are some significant divergences, as GCAM has an internal land-use module, which is the one that determines the regional production levels. In terms of RYLs, USA shows the largest differences, as the damage coefficients estimated in this study are far greater than the values published in literature. The main reason is the overestimation of O_3 precursor emissions in GCAM. For example, GCAM NOx emissions in USA significantly outweigh the EPA-inventory emissions, as demonstrated in Shi et al., (2017). On the other hand, the largest divergences in economic damages is found for oilcrops, which almost triples the values from previous studies. There are two factors which explain this significant difference: the RYLs overestimation in some regions (such as USA and India) and the larger production levels[16] (both globally and regionally) for this crop.

In terms of future projections, results are not directly comparable since there exist significant differences in the model used, the scenario definition or assumptions in future development levels. However, there are some similarities. First, Van Dingenen et al. (2009) shows that future changes in RYLs up to 2030 would vary depending on the region: they would increase in South-Asia (India or Bangladesh) while decrease in Europe or China. Similarly, Chuwah et al. (2015) conclude that that larger O_3 levels in Asian regions would imply a substantial increment of crop-oriented land requirement (up to 9%). As shown in Figure 2.5 , those results are similar to the ones obtained in this chapter for South Asia, In those studies, O_3 impacts are calculated using exposure-response functions (ERF). These ERF models have some limitations. On the one hand, they do not capture vegetation dynamics, so they do not take into consideration physiological factors such as soil particularities, vapor pressure, transpiration or evaporation, as described in Schauberger et al., 2019. That study concludes that, in places with water scarcity, the O_3 impacts on crops would be overestimated, while underestimated in water abundant regions. Consequently, the estimation of regional RYLs would also differ depending on the applied methodology. For example, the developed study shows significantly smaller RYLs values for wheat in both China and India, compared to results in Schauberger et al., 2019; however, the RYLs for soybeans are notably larger when applying ERF models than when considering the whole vegetation system.

On the other hand, the ERFs are based on European and North American information. The lack of data for calculating the ERFs in other regions would result in a significant underestimation of the O_3 driven crop losses in Asian regions (Emberson et al., 2009). Recent studies are focusing on regional and national emission data in order to more accurately estimate the O_3 impacts on crops (Feng et al., 2017).

Additionally, ERFs have only been to four crops and then extend the damages to further commodities based on their carbon fixation pathway (see *methodology*). Although there are well-accepted ERF functions for other crops (Mills et al., 2007), the structure of the GCAM model, which combines commodities in aggregated groups, does not allow to apply those individualized functions. This is planned to be explored in further research. Furthermore, other harmful effects such as climate impacts are not captured, measured as temperature or precipitation changes, or carbon fertilization effects, that have demonstrated implications on yields (Shindell et al 2019). Those variables would produce some feedbacks that are not possible

[16] Previous studies analyze soybean damages while this study oilcrops. This GCAM category includes soybeans but some other commodities (see Annex II), therefore the differences in production would be even larger.

to be considered with the applied methodology. Further research will combine those effects in order to provide a wider perspective of the potential crop damages.

Conclusion

This chapter analyzes the implications of O_3 on different crops both globally and regionally. First, it is examined which would be the distribution of O_3 concentration levels up to 2080. For that purpose, the emission pathways of its main precursors are estimated, which are NOx and CH_4. CH_4 emissions would significantly increase in the baseline scenario (with the exception of some countries such as Brazil or China), while NOx emissions follow a stable or decreasing trends due to the implicit implementation of emission-control policies. However, the absolute future emissions per region vary substantially, resulting in significantly different O_3 formation per region. Additionally, in those regions that are closer to the equator belt, O_3 levels would be even larger, as solar radiation is a key factor for the formation of this pollutant.

In a next step, the estimated O_3 concentration levels are set into ERFs in order to calculate the potential crop damages for four representative commodities such as corn, oilcrop (soybeans), rice and wheat. Wheat and soybeans are the most sensitive crops while corn and rice present smaller RYLs. Regions such as India, USA, Europe or Africa Northern suffer the largest RYL values, depending on the crop.

Finally, the obtained O_3 damage coefficients are introduced into the GCAM model, in order to compare the obtained results with the ones from a default baseline (no O_3 effects) scenario, so the implications in agricultural market dynamics are observed. Production of corn and wheat remains relatively unaltered as the estimated increases in yield productivities are softened by a smaller demand response. Moreover, reduced O_3 effects decrease economic damages for both corn and wheat by 2080. Oilcrop production would significantly increase due to the smaller future O_3 levels, and due to an increased use of these crops for energy purposes. Regarding rice crops, the differences are driven by results in India. While there is a decrease in yield productivity, it does not translate to demand and the production remains relatively unaltered, with a subsequent increase on the amount of land for rice production. In terms of economic damages, the increase in O_3 concentration levels, driven by the positive trend of CH_4 emissions, would increase the estimated economic damages.

Chapter 3

Implications of switching fossil fuel subsidies to solar: A case study for the European Union

Introduction

The main goal of the Paris Climate Agreement (UNFCC) is to ensure that the average global temperature increase does not exceed the threshold of 2°C or 1.5°C above preindustrial levels. To that end, greenhouse gas (GHG) emissions need to peak "as soon as possible" and then be reduced practically to zero in the second half of this century (IPCC., 2014). Currently, fossil sources account for 80% of the global total primary energy supply and 60% of global greenhouse gas (GHG) emissions (IEA 2016). Therefore, an urgent and far-reaching transformation in the energy system will be required, where fossil fuels are gradually phased out of the energy mix, especially coal, which is the most CO_2-emission-intensive fuel of all in terms of energy content.

There are many different regulatory and economic instruments that can be used to boost this transition towards a low-carbon economy. From the economic perspective, one of the most urgent measures should be the elimination of fossil fuel subsidies (FFS), since they encourage inefficient energy consumption and divert investment away from clean energy sources. According to the International Monetary Fund (IMF) (Coady et al., 2017) FFS amounted globally to $233 billion in 2015.The elimination of FFS would not only be beneficial from the climate change perspective (these subsidies work in practice as a negative carbon price) but would also help to eliminate a significant market distortion that encourages inefficient consumption and does not, as it is sometimes perceived to do, benefit the poorest. According to the IMF, these subsidies tend to be regressive as only 7% of subsidies in developing countries actually reach the poorest 20% of households, while 43% end up in the hands of the richest 20%. For all these reasons, the International Energy Agency (IEA) has proposed a phase-out of FFS as one of the key elements for enabling society to move to a low carbon economy. In this regard, at their meeting in Ishe-Shima (G7 Leaders, 2016) the G7 leaders pledged to phase out fossil fuel subsidies by 2025.

In this context, there is emerging interest among the scientific community in the potential environmental, economic and social implications of phasing-out FFS. Ellis (2010) provides a survey of the literature that has sought to quantify the economic and environmental consequences of fossil fuel subsidies at global level. These studies conclude that a phase-out of FFS would reduce world GHG emissions in the longer term, although the magnitude differs greatly from one study to another, ranging from 0.6% (Schwanitz et al., 2014) to 10% (Burniaux and Chateau, 2014; WEO 2017). In general, studies based on economic models (partial or general equilibrium models) tend to obtain higher emission reductions than integrated assessment models of the energy-system and the economy, as they tend to be more optimistic in terms of fuel-switching possibilities[17]. Schwanitz et al. (2014) use the REMIND integrated assessment model and show that in the long-term the removal of fossil fuel subsidies would only result in emission reductions of around 0.6%. Most remarkably, they show that if it is not supplemented by other policies, the removal of fossil fuel subsidies may actually increase emissions in some countries. The reason is that the induced change in global energy prices and the lack of alternatives in many countries may eventually lead to an increase of coal consumption and the use of coal-to-liquids conversion technologies. Therefore, the phase-out of fossil fuel subsidies needs to be designed and implemented carefully and must take into

[17] For example, CGE models typically use a highly aggregated constant elasticity substitution (CES) function to capture the elasticity substitution between fossil fuels. Although some models include more detail in the electricity sector this is rarely the case in the transport sector.

consideration the substitution possibilities available in each specific region/country (Burniaux and Chateau, 2014).

This study uses GCAM to analyze the CO_2 reduction potential when the revenues from the elimination of FFS are used to promote renewables, and more specifically solar technologies. Although there are some studies that suggest that IAMs are not the most accurate tool to analyze short-term changes or shocks (Pietzcker et al., 2017), this work focuses on which would be the global (including energy, land use or climate systems) situation in 2030, so to use such an integrated instrument provides insights to the framework. The *methodology* subsection provides detailed information about the features of the applied GCAM.

The analysis focuses on the European Union (EU), which is a relevant case study for two reasons. First, the EU has already committed (see Council Decision, 2010/787/EU) to eliminating coal subsidies in all Member States by 2018[18]. In fact, coal subsidies are large in the EU, accounting for around 81% of global subsidies. Second, the EU has also set a specific target for renewables (at least 27% of final energy should come from renewable sources by 2030, (EC SWD, 2014), which also justifies the "recycling" of the revenues from FFS to renewables.

The chapter is organized as follows: the following subsection presents the materials used in the study (including the data on FFS, and the scenarios); then, the results are shown and finally the subsequent subsections discuss the obtained results and conclude, respectively.

Study Design

Data

This subsection presents an overview of FFS at global level and for the EU as estimated by the IMF (Koplow, 2009). The estimations by the IMF follow a price-gap approach[19] (Clements et al., 2013; Coady et al., 2017) that calculates subsidies by multiplying fuel consumption by the difference between end-user prices and supply costs[20] (or private costs). This gives the so-called "pre-tax" subsidies or FFS which have to be financed directly from government budgets. On the IMF database there are two main approaches reported: on the one hand, the mentioned "pre-tax" or direct monetized subsidies that account for US$233 billion in 2015 for FFS. On the other hand, "post-tax" subsidies, which also include the negative externalities from energy consumption, would account for around $5 trillion. This work focuses on the pre-tax subsidies.

[18] Although there are some doubts whether all Member States will implement this directive (for example some countries such as Germany or Spain are introducing new mechanisms that provide payment to coal-fired plants to provide a supply of electricity with domestic coal), this directive focuses on the elimination of "inefficient coal mine" subsidies.

[19] The International Energy Agency follows the same approach (IEA 2015) and obtains similar results. However, the Organization for Economic Co-operation and Development (OECD) follows the so-called "inventory approach", which captures the direct budgetary support and tax expenditures on fossil fuel production or consumption. The OECD database applies only to 34 OECD countries.

[20] The IMF methodology also includes shipping costs and margins, plus value added taxes. The IEA also includes some tax subsidies, which is one reason for the difference between IEA and IMF estimations for pre-tax subsidies.

The data reported here and used in the study are based on FFS estimated for coal, petroleum and gas[21].

In 2015, FFS amounted globally to US$233 billion, which is 37% down on the figure for 2011. This reduction in FFS reflects the fall in international energy prices and the reduction in FFS already undertaken in some countries such as Saudi Arabia, the United Arab Emirates and Indonesia (Davis, 2016; Durand-Lasserve et al., 2015). It should be mentioned that the historical trend in FFS may not be a suitable indicator for showing government attitudes towards promoting fossil fuels, as it is also affected by changes in energy prices and other macroeconomic conditions. However, FFS accounted for 0.41% of global GDP, which is still an economically significant figure, and in many countries they represent a major share of the government budget.

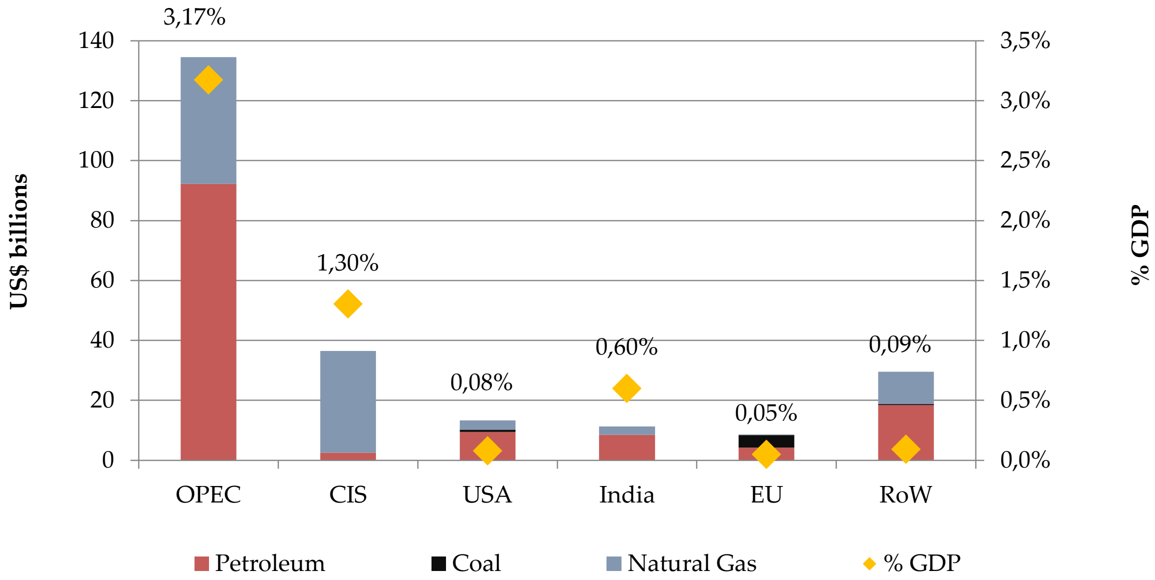
Figure 3.1 shows the breakdown of FFS by regions and fuels. Most subsidies are concentrated in energy-exporting countries. The OPEC[22] (Organization of the Petroleum Exporting Countries) and CIS[23] (Commonwealth of Independent States) countries account for 73% of the world's FFS. Adding the USA, India and the EU, the proportion of world FFS accounted for rises to 87%. As far as fuel sources are concerned, by far the most heavily subsidized fuel is oil (US$127 billion), followed by natural gas (US$89 billion) and coal (US$5.09 billion). In terms of FFS relative to GDP, the highest average absolute figure is that of OPEC countries with 3.17%, followed by the CIS countries (1.3%) and India (0.6%).

[21] Subsidies for electricity consumption are not considered in this study. The IMF database does not break down subsidies for electricity into different sources, so it is not possible to allocate those subsidies to fossil or nom-fossil fuel sources such as renewables or nuclear.

[22] OPEC comprises Algeria, Angola, Ecuador, Gabon, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates and Venezuela

[23] The CIS (Commonwealth of Independent States) comprises Russia, Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan and Uzbekistan, with Turkmenistan and Ukraine as associate members.

Figure 3.1: World fossil fuel subsidies by regions and fuels (US$ billion and %GDP). Source: IMF



In the EU, FFS are not as high as elsewhere. In 2015, FFS in the EU amounted to US$8.63 billion (3.69 % of global subsidies). The EU has comparatively low subsidies on oil (US$4.3 billion) and gas (US$0.3 billions), but its subsidies on coal (the most intensive fuel in terms of CO_2) are very high (US$4.1 billions) and account for a striking 81% of world coal subsidies. As a member of the G7 group, the EU has agreed to eliminate all forms of support for fossil fuels by 2025.

Scenario Schemes

The main purpose of the chapter is to explore the impacts of removing FFS in the EU and "recycling" the savings to subsidize solar energy. This subsection presents the scenarios of the different fossil fuel subsidy reforms. The three scenarios are summarized as follows:

Table 3.1: Scenario description

Scenario	Description
Baseline	This is the reference scenario in which there is no climate policy in place. In this scenario subsidies on fossil fuel are included in the base year (2015) as a negative cost in unitary terms ($ per GJ). Unitary subsidies are assumed to remain constant throughout the simulation period. The amount of money spent on subsidies can then be obtained in each period by multiplying by the consumption of fossil fuel.
Phase-out	This scenario phases out subsidies on fossil fuels in the EU. However, the revenues are not reinvested in promoting low carbon technologies.
Recycling	This scenario phases out FFS and reinvests them in renewables, more specifically in solar rooftop photovoltaic[24] (hereinafter, rooftop PV). The rooftop PV option is selected for three main reasons. First, the government can directly promote this technology without interfering in other policies such as in the new renewable energy capacity auction-based system (EC, 2014) or the EU emission trading system (EU-ETS) (Böhringer et al., 2008).On the other hand, investments in rooftop PV also enable small actors to participate, such as municipalities, small business and individuals[25]. Finally, the other main renewable alternative, wind energy, is starting to bid at zero[26] subsidy cost, which means that some renewable technologies are closer to competing with other technologies at market prices. In any case, a sensitivity analysis is shown to demonstrate the CO_2 mitigation potential of using other renewable technology options.

As the renewable energy system has been supported by different financing mechanisms over the last years, it is important to reflect the important magnitude of this mentioned "recycling" process. Latest estimation on subsidies to renewable power sector accounts for US$120 billion (Clements et al., 2013), so taking into account that the used number for FFS subsidies is US$233 billion, it would almost double that amount.

[24] The subsidized rooftop PV technology is an off-grid electricity system, which is directly competing with grid-based electricity. The industrial photovoltaics are not taken into consideration in these results.

[25] Although there are more technological options that allow small participants (micro-wind installations), rooftop PV presents the highest level of development.

[26] In a recent auction of 500MW of wind energy in Spain all the capacity was acquired at bids of zero – meaning that no financial support is required.

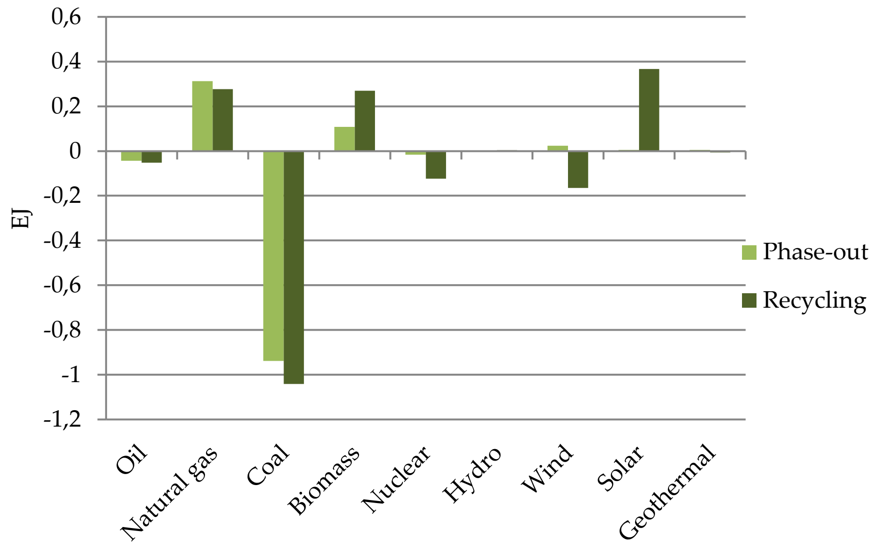
Results

This subsection presents implications of eliminating FFS in the different scenarios by 2030 for the energy system, CO_2 emissions and mitigation costs and air pollution, scenarios with and without recycling of revenues from subsidies. The results include a sensitivity analysis for different FFS recycling options.

Energy and electricity system

Figure 3.2 shows the absolute variations in primary energy consumption of the scenarios with respect to the baseline.

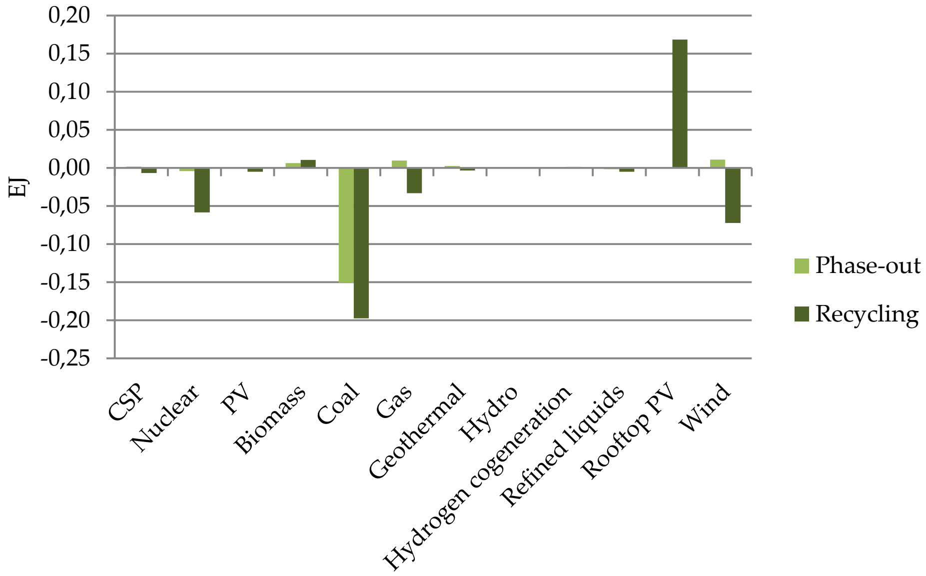
Figure 3.2: Differences in primary energy consumption in 2030 in EU (EJ) with respect to the baseline scenario



The most important reduction observed in both scenarios is in coal consumption, with drops of 6.3% and 7% by 2030 respectively. This is because coal, which is mainly used in electricity generation and industrial processes, can easily be replaced by other fuel sources. Indeed, natural gas consumption increases by 1.5 and 1.3% by 2030 with the elimination of the subsidies. This happens because the subsidies for natural gas are relatively smaller than the ones for coal, so, according to the model assumptions, gas would become comparatively more competitive and may replace coal in some sectors.

The effect on oil consumption is however very limited, with reductions of 0.16 and 0.19%. Oil is mainly used in the transport sector and, according to the model, the use of alternatives such as biofuels and electric vehicles due to the elimination of oil subsidies is limited, given the high costs for these alternatives. Another consequence is that in the recycling scenario, where rooftop PV penetrates the market strongly, other technologies such as nuclear and wind energy decrease.

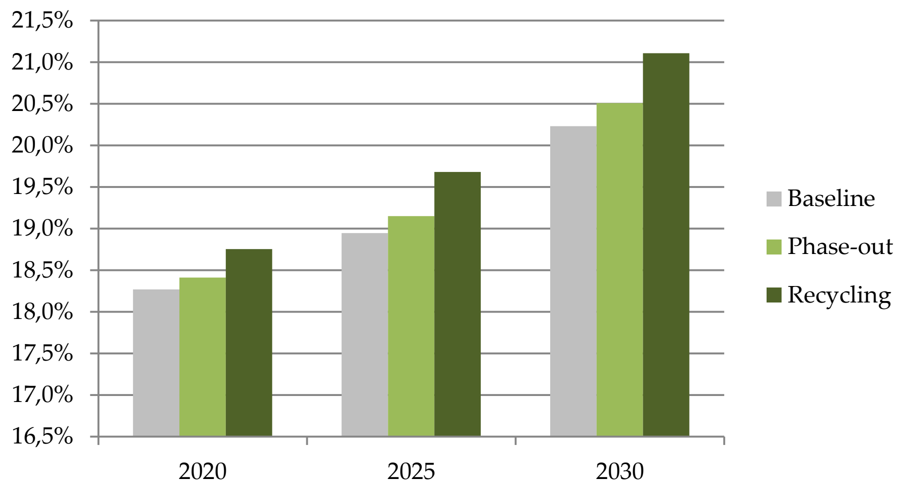
Figure 3.3: Differences in electricity mix in EU in 2030 (EJ) with respect to baseline scenario



In order to provide a better understanding of the changes in the energy system, Figure 3.3 shows the change in the electricity mix with respect to the baseline scenario. The results are consistent with those already explained for the primary energy mix. However, there are some aspects that deserve closer attention. First, the use of biomass in the electricity sector is not substantially modified. Similarly, the electricity generated from gas-fired plants does not increase despite the major deployment of gas as an energy source (see Figure 3.2). This is because the subsidized rooftop PV replaces fossil fuels (mostly coal) in the electricity sector, whereas biomass and gas replace coal and oil in other sectors (such as industry, buildings or to a lesser extent transport). Additionally, wind and solar are considered as intermittent technologies, so to ensure that electricity demand can be met at any time (including "peak loads") the expansion of solar would replace some use of wind energy. This effect would be ameliorated if the cost of storage batteries were lower. Finally, there is a decrease of nuclear power that can be explained with the need for backup support that solar energy requires (due to the intermittency). Since the recycling scenario presents an energy mix with a higher share of renewable energy and nuclear energy cannot be used as backup for the increased solar power (nuclear power stations cannot be switched on-off easily), it is less extended than in the baseline scenario. The deployment of rooftop PV is quite limited in both the baseline and FFS phase-out scenarios. However, in the scenario where all FFS are switched to rooftop PV the production of rooftop solar electricity increases with 0.17 EJ by 2030, which represents a doubling of rooftop solar electricity production compared to production in 2015.

Finally, the elimination of FFS would also help meet the EU's targets on renewables. Figure 3.4 shows what the share of renewable sources would be in each scenario. In the baseline scenario the projected share of renewables in the electricity mix in the EU by 2030 is 20.23%. This share is greater in both the Phase-out (20.51%) and Recycling (21.11%) scenarios. These results are still far from the target for renewable energy (27% of the energy mix), but it is worth mentioning that the increase is being achieved at zero extra cost for the government.

Figure 3.4: Share of renewable energy sources in the EU electricity mix per period

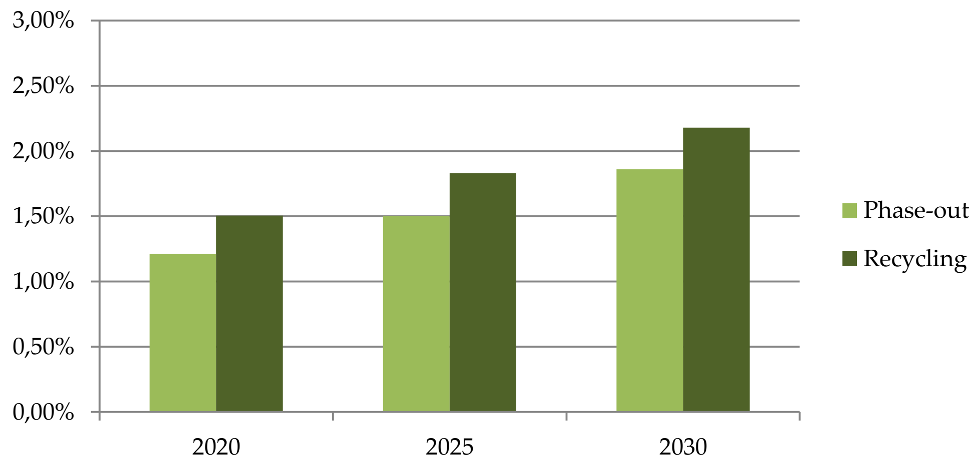


CO_2 emissions and mitigation costs

This subsection shows the implications of the different scenarios in terms of CO_2 emissions, taking into consideration both emission reduction and mitigation costs. A sensitivity analysis is also presented here to assess the effect of recycling FFS to promote other renewable technologies.

Figure 3.5 analyzes CO_2 emissions per period in each scenario up to 2030 as percentage variations with respect to the baseline scenario. If FFS are merely eliminated ("Phase-out" scenario), emissions decrease by up to 1.8% by 2030. However, when the subsidies are taken and reinvested in rooftop PV emissions decrease by 2.2% by 2030, a relative increase of 21%.

Figure 3.5: Percentage reduction of CO_2 emissions per period (%)



Due to variations in the penetration of the technologies, the abatement cost differs from one scenario to another. To put the numbers in context, the abatement cost of the recycling scenario is compared with the current EU policy, which is to achieve a 40% CO_2 reduction by 2030. Indeed, it is estimated that the FFS reform would cover 3% of the mitigation cost needed to meet the European target of a 40% CO_2 emission reduction by 2030[27].

Lastly, to show the mitigation potential of recycling the revenues to promote other renewable options, and following the same methodology and assumptions, Table 3.2 shows the CO_2 mitigation achieved with different technologies relative to the baseline scenario. It can be seen that reinvesting FFS to promote other renewable sources can increase CO_2 mitigation by 3-3.5%. These figures result from the lower costs of other renewable technologies compared to rooftop PV. However, our focus on rooftop PV is based on the advantages that this technology has for implementation reasons. As shown, direct investments in rooftop PV help to avoid certain regulatory problems such as market distortions (EU-ETS) and facilitate the entry of other, smaller participants (municipalities or individuals).

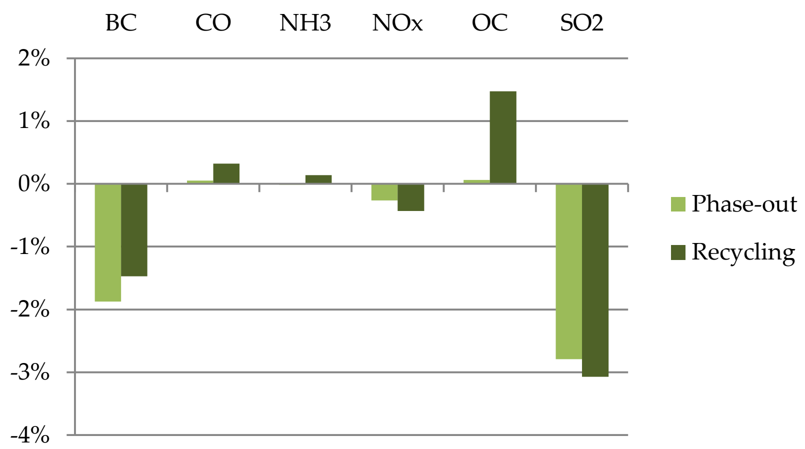
Table 3.2:Sensitivity analysis on CO_2 mitigation potential using different renewable technologies (%)

TOTAL PROJECTED REDUCTIONS (%)	2020	2025	2030
Rooftop PV	1.5%	1.8%	2.2%
Other solar (CSP and utility-scale PV)	1.9%	2.2%	2.6%
Wind	2.6%	3.1%	3.4%

Air Pollution

The implications of other air pollutants have become a key element in the analysis of climate policies (West et al., 2013a). In this study some of the main air pollutants have been considered: black carbon (BC)[28] carbon monoxide (CO), ammonia (NH_3), nitrogen oxides (NOx), organic carbon (OC) and sulfur dioxide (SO_2).

Figure 3.6:Differences in air pollutants in EU-27 in 2030 (%)



[27] The cost of the EU policy is also calculated by setting the mitigation target in GCAM.GCAM provides the cost of the simulated policy and, according to the model assumptions, the average abatement cost ($/tCO2) increases with the stringency of the policy established. In the recycling scenario the cost is around $96.7/tCO2 in 2030, while when simulating the mentioned EU policy, it is $419/tCO2

[28] Although BC has a demonstrated greenhouse effect (Shindell et al., 2012) it is also a $PM_{2.5}$ precursor, so it is considered an air pollutant.

Figure 3.6 shows the variation with respect to the baseline in some of the main pollutants for the different scenarios. In the "Phase-out" scenario SO_2 emissions show the biggest reduction (-2.8%). In Recycling, SO_2 emissions show an additional effect and drop by 3.1%. More and more studies are analyzing the implications of climate and energy policies for SO_2 (Nemet et al., 2010), as it is one of the main contributors to the damage associated with air pollution. On the one hand, exposure to SO_2 has implications for health due to its effect on circulatory and respiratory systems, especially among children and older people. On the other hand, BC and SO_2 have both direct and indirect effects: after being emitted they are among the main precursors for the formation of particulate matter (both PM_{10} and $PM_{2.5}$). As shown, exposure to high concentrations of PM is considered as a major risk factor in terms of health impacts.

However, when FFS are reinvested the increase in biomass consumption results in an increment of CO and OC. Although the figures show not very high increments (0.32 and 1.47% respectively), it is important to realize that they could entail some indirect damage. For instance, CO is a precursor for the formation of tropospheric ozone (O_3), which has been proven to have impacts on health (Jerrett et al., 2009; Turner et al., 2016) and agricultural systems (Chuwah et al., 2015). Moreover, OC emissions are also a key element for the deposition of $PM_{2.5}$ in the atmosphere.

Therefore, this policy would not achieve significant health co-benefits: first, the absolute changes in pollutant reductions are relatively small and, second, the decrease in some pollutants (f.e. SO_2, -3%), which would reduce health damages, would be compensated by the increase in the emissions of carbon monoxide (CO) or organic carbon (OC), related to the expansion of bioenergy technologies.

Discussion

This simulation exercise has certain limitations but it also opens up further research questions, which are discussed in this subsection. The most important one is that the results depend on the projections of the baseline scenario. As shown, CO_2 emission reduction could be between 1.5% and 3.5% if there is no other climate policy in place in the region, but this result could change if there is a climate policy already in place. In any event, it has been shown that FFS recycling always has a positive impact in terms of renewable energy penetration and emission reduction.

Another important issue is that in Europe there are sectors where there is already a mechanism in place to reduce CO2 emissions. The "EU-ETS" cap and trade system is the most important such mechanism, covering around 45% of all GHG emissions in the region. FFS recycling could therefore lead to overlapping regulation problems. However, as presented, this limitation could be reduced by switching subsidies to renewable technologies that do not affect the system, such as directly subsidising rooftop photovoltaic facilities.

On the other hand, most previous studies in this field have used General Equilibrium Models (Arze del Granado et al., 2010; Davis, 2016). Such models focus on welfare or distributional analysis or price implications of removing FFS. Among their results, it can be highlighted that FFS are inefficient as a policy instrument for protecting poor households from fuel price increases. It would be interesting to see if removing FFS proves to be a regressive policy due to the possible increase in electricity prices. Additionally, using GCAM instead of another type of model, makes it impossible to analyze macroeconomic indicators such as possible industrial losses, employment effects or welfare variations.

Work has also been done in relation to investing FFS savings (Jakob and Hilaire, 2015), and some authors suggest creating an international fund in order to reallocate possible revenues. According to these authors, if the global savings (of oil importers) were reinvested a positive economic transformation would be achieved. This paper analyzes only the case of the EU: the amount of money saved from subsidies is directly reinvested in cleaner energy sources with the EU. However, an interesting line for further research would be to check the implications of using that money to promote mitigation options outside the EU.

Finally, there could be several barriers to applying the policy proposed here. The study focuses on reinvesting Member State subsidies at an EU region level, but the differences between the 27 European countries would make such an agreement complicated given the concentration of subsidies in specific countries (such as Germany and Poland).

Conclusion

This chapter estimates potential impacts of removing fossil fuel subsidies (FFS) in the EU and "recycling" the savings to subsidize solar energy directly (rooftop PV). Although removing FFS in EU does not suffice in itself to achieve major emission reductions - which is also an important result - the recycling of these subsidies to promote low-carbon technologies can generate additional positive effects. The most interesting is related to the additional penetration of renewable technologies: it is shown that if FFS is reinvested in rooftop PV, the installed capacity of this technology could present a significant increase according to the assumptions of the model.

As shown, if no additional climate policy is established FFS recycling could result in a CO_2 emission reduction of between 1.5 and 3.5%. Therefore, taking into consideration that this is only a first step towards meeting European CO_2 targets, FFS recycling should be considered as a valuable policy. Even though there are other climate policies that may entail higher CO_2 decreases, they could require substantial investments and long implementation periods, while the elimination and recycling of FFS is budget neutral and can be implemented very fast and at zero-cost.

It is also clear that deploying such a policy around the world would need hard cooperation and negotiation processes. Nevertheless, many countries have started taking measures in this area (Clements et al., 2013), so existing results and experiences could help in the implementation processes.

Chapter 4

Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study

Introduction

The two main health-harmful air pollutants linked to fossil fuel combustion and greenhouse gas (GHG) emissions are fine particulate matter ($PM_{2.5}$)(Burnett et al., 2014; Klimont et al., 2017; Silva et al., 2017); and ozone, (O_3)(Jerrett et al., 2009; Turner et al., 2016). In this context, the Paris agreement, which aims to significantly reduce fossil fuel use, has major health implications. The agreement aims at a long term stabilization target of 2°C and agrees to pursue efforts to limit the increase to 1.5°C.(Rogelj et al., 2016).

Concrete measures to achieve these targets have not yet been agreed. A key concern when evaluating different climate policies is their net cost[29], with a key component of overall policy cost being the associated co-benefits.(Radu et al., 2016; Chowdhury et al., 2018; Landrigan et al., 2017; West et al., 2017, 2013) Co-benefits are defined as additional benefits related to the reduction of greenhouse gas emissions that are not directly related to climate change, such as air quality improvement, technological innovation or employment creation.(Bollen, 2015)

One of the key challenges related to the Paris goals is how to share the mitigation efforts for meeting the target. The higher the ambition of the mitigation objectives the more difficult the distribution of targets across countries.(Jacoby et al., 2008; Raupach et al., 2014) It is well known that the current national mitigation targets reported by the different countries to the United Nations in their Nationally Determined Contributions are not enough,(Fawcett et al., 2015) and, if they are not raised, one can expect a temperature increase by the end of the century of between 2.9-3.4°C.

Health co-benefits of mitigation have been explored in the literature. The major gaps in the current literature are a failure to look at co-benefits by region given the range of different allocations of mitigation burdens; and an evaluation of the co-benefits relative to mitigation costs for the 1.5°C target. This chapter compares, both at the global and regional level, a range of climate mitigation scenarios in terms of air pollution and health impacts, and determines to what extent the extra cost of achieving a more restrictive mitigation target could be compensated with the obtained additional health co-benefits, both global and regionally.

As detailed in *methodology*, the analysis consists of three steps. First, GCAM is used to quantify the GHG pathways and the related mitigation costs of the different scenarios. GCAM also reports the emissions of air pollutants in the different regions. This information is fed to the TM5-FASST air quality source-receptor model, which translates emission levels into pollutant concentrations, exposure and premature deaths. These deaths are then monetized using the Value of Statistical Life (VSL) with the valuation extended to incorporate morbidity effects.

Scenarios

The scenarios have three main components:1) a general socioeconomic storyline represented by the Shared Socioeconomic Pathways of the IPCC framework,(O'Neill et al., 2014; van Vuuren et al., 2017) 2) a model quantification of that storyline, and, 3) a set of mitigation strategies based on du Pont et al. (2016) where current national mitigation targets are extended based on different equity criteria to allocate the carbon budgets for different temperature stabilization objectives.

[29] This chapter uses the term mitigation cost to refer to the direct costs of reducing GHGs and policy costs to refer to the overall costs when any co-benefits have been taken into account. Avoided climate damages are not calculated by the models used here.

The background socioeconomic conditions are a key element of the analysis giving baseline values for population and GDP in each country over time. The socioeconomic scenario chosen here (SSP2) is considered a "middle of the road" framework (van Vuuren et al., 2017). A complete description about the features and implementation of this scenario can be found in Annex IV. The SSP database[30], hosted by IIASA, provides the country-level population figures used by TM5-FASST and the GDP figures, which are inputs to estimate monetarized damage by VSL. Both population and GDP are also used by the GCAM model in combination with additional assumptions regarding the economic structure, and energy and agricultural systems.(Rao et al., 2017; Riahi et al., 2016). The study takes the SSP2 emission factors for calculating the air pollutant emission trajectories as released with GCAM v4.3. While updated versions were used in published GCAM scenarios,(Calvin et al., 2017) the changes do not impact the overall conclusions of the paper (Annex IV). Moreover, the annex also examines the impact of alternative socioeconomic pathways on emission trajectories.

The mitigation strategies are divided following two criteria: the global temperature target and the regional distribution of the mitigation effort associated with each target. Regarding the temperature target, in addition to a baseline scenario where no climate policy is set, three scenarios have been chosen: (a) the Nationally Determined Contributions (hereinafter NDCs), (b) 2°C stabilization target and (c) 1.5°C stabilization target (both objectives for the year 2100).

Regarding the regional distribution of mitigation effort, du Pont et al (2016) suggests five distributional approaches, of which three have been selected. They are summarized in Table 4.1[31].

Table 4.1: Mitigation equity criteria. Source: http://paris-equity-check.org

Allocation name	Code	IPCC Category	Allocation characteristics
Constant emission ratios	CER	Staged approach	Maintains current emission ratios, preserves status quo. This approach also referred to as grandfathering, is not considered as an equitable option in climate justice and is not supported as such by any Party.
Capability	CAP	Capability	Countries with high GDP per capita have low emissions allocations
Equal per capita	EPC	Equality	Convergence towards equal annual emissions per person by 2040

Following du Pont et al (2016), the world is divided into five regions: China, EU-27, India, USA (which covers 60% of global emissions in 2015) and the rest of the world (ROW). Also, following the same literature, the results are presented until 2050.

Although each scenario has a similar global carbon budget to 2100 the carbon budgets to 2050 are different as the criteria selected affect also the timing of mitigation. Figure 4.1 shows notable differences in CO_2 emissions pathways. In the NDCs scenario the emissions are reduced by around 25% with respect to the baseline by 2050. Although significant, it is not sufficient to achieve the Paris climate target. Compared to the NDCs scenario, the 2°C scenarios require a

[30] https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

[31] The two excluded allocations are ones involving very unequal allocations to developed countries. Moreover, they require huge negative emissions to be realized, which is unrealistic.

reduction in CO_2 emissions across the five regions ranging from -71% to +57%. Logically, the reduction in the 1.5°C scenarios is greater, ranging from -79% to +8%, depending on the criterion for sharing the mitigation effort.

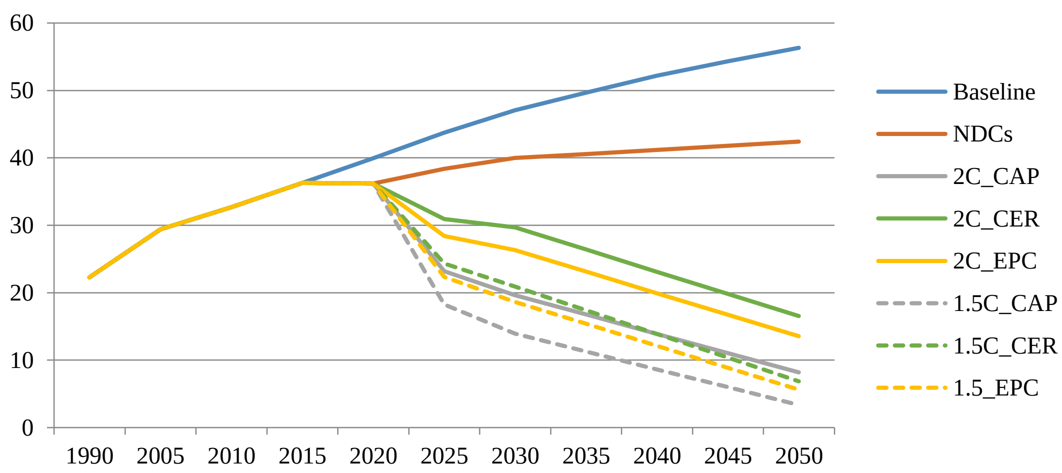
While the restrictiveness of the climate target is an important factor in explaining the variations, the distributional criterion is also important. As Figure 4.1 shows, the reduction in emissions out to 2050 is greatest under the CAP scenario and least under the CER scenario. These differences translate into different mitigation efforts for the regions. Table 4.2 shows the cumulative emissions reductions for different regions relative to their commitments under the NDC.

Table 4.2: Variation in 2020-2050 cumulative emissions relative to the NDC scenario (%)

	2C_CAP	2C_CER	2C_EPC	1.5C_CAP	1.5C_CER	1.5C_EPC
China	-69%	-35%	-52%	-75%	-54%	-65%
USA	-40%	57%	-16%	-52%	8%	-37%
EU-27	-43%	35%	-4%	-55%	-7%	-31%
India	-60%	-71%	-36%	-72%	-79%	-58%
ROW	-50%	-47%	-46%	-64%	-63%	-62%
Total	-55%	-35%	-42%	-67%	-55%	-59%

It is notable that China has to make a further 69% reduction under the CAP scenario, but only 35% under the CER scenario. The CER scenario imposes the greatest burden on India, and allows the USA and the EU-27 to reduce emissions by 57% and 34% less than they have committed to under the NDCs.

Figure 4.1:Total CO2 emissions per period and scenario (GtCO2)



Results

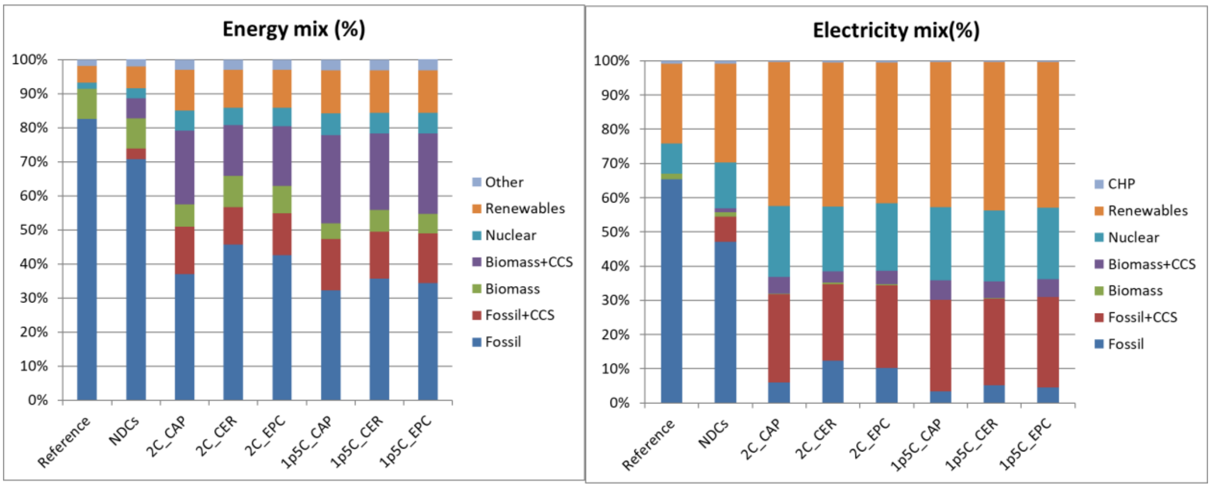
Energy and electricity system

The differences on the stringency and the effort sharing among the scenarios result in different energy mixes for 2050. The main difference between the scenarios is the share of fossil fuels, which decreases as the mitigation target becomes more stringent. While in the baseline scenario the fossil fuels account for around 82% of the energy mix in 2050, this falls to 37-45% in the 2°C scenarios and to 32-36% in the 1.5°C.

This reduction is compensated with a higher development of low-carbon technologies. First, the implementation of mitigation policies increases the share of biomass in the energy mix (Biomass and Biomass+CCS). From 9% in the baseline scenario, to 15% in the NDC's, to 24-28% in the 2°C and to 28-30% in the 1.5°C. The share of other renewable technologies (solar, wind and geothermal) also increases, though the differences between 2°C and 1.5°C scenarios are not so high: renewals go from around 5% in the baseline to 6.4% in the NDCs scenarios and to 11-12% and 12-13% in the 2°C and 1.5°C scenarios respectively. Finally, there is also a smaller increase in nuclear power, from 2% to around 5-6% in the more restrictive mitigation scenarios.

The changes in the electricity mix are even more significant, with a huge drop in the use of fossil fuels for electricity from 65% in the baseline to 6-12% in the 2°C scenarios and 3-5% in the 1.5°C. There is also a relevant expansion of renewables (from around 10% in the baseline to more than 40%) and CCS (representing between 25 and 32% in the 2°C and 1.5°C scenarios).

Figure 4.2:Energy and electricity mix per scenario in 2050 (%)



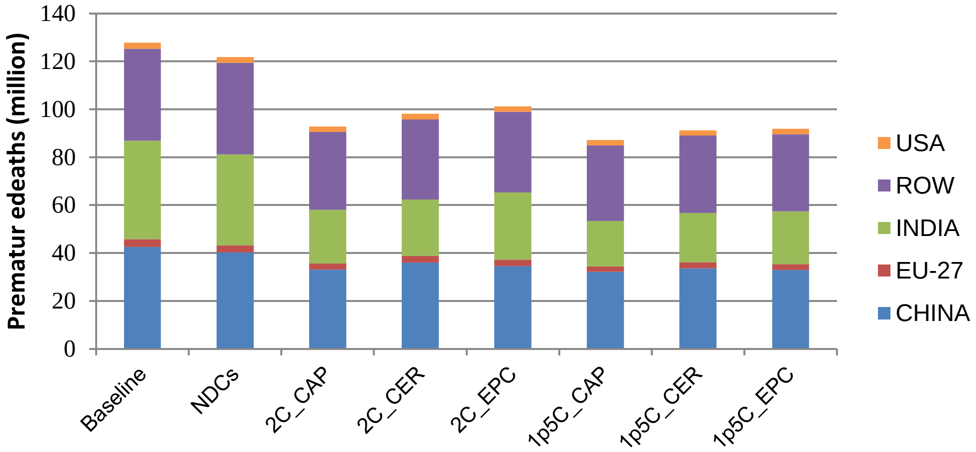
CCS: Carbon Capture and Storage.

Premature deaths

Figure 4.3 reports the cumulative premature deaths for each scenario. Globally, this cumulative number shows a significant decrease in going from the reference scenario to the 2°C and 1.5°C. In the NDC scenario the number of deaths decreases around 5% relative to the reference, while the reductions for the mitigation scenarios are 21-27% and 28-32% for the 2°C and 1.5°C respectively.

Each region presents similar relative results regardless of the scenario analyzed. The highest number of premature deaths are in China (33-37% of the global deaths) and India (24-32%). Around 37% of the global population lives there and most of it is exposed to pollution levels far above the recommendations guidelines from World Health Organization.

Figure 4.3: Cumulative (2020-2050) premature deaths per region and scenario (million people)



Mitigation and Policy Cost

The results for the mitigation cost for the defined scenarios32 and regions are given in Table 4.3[33].

The table has some quite contrasting results:

i. Under "CAP" China bears most of the cost, followed by the rest of the world (ROW). India has the lowest cost share.
ii. The ranking changes significantly under "CER", with India now having a much higher share and China much lower one.
iii. Compared to what countries have committed to under the NDCs, the increases in costs are smallest for the USA and EU-27 and biggest for the ROW, India and China (in that order).
iv. The additional cost of going from a 2°C target to a 1.5°C target is around 20%.

[32] The "baseline" scenario is not included since is not supposed to have any policy cost.
[33] The "baseline" scenario is not included since is not supposed to have any policy cost.

Table 4.3:Cumulative (2020-2050) policy cost per region and scenario. The table shows the percentage of global mitigation cost borne by each region. The value in parenthesis gives the absolute mitigation cost in trillion$. The discount rate used for the calculation is 3%.

	NDCs	2C_CAP	2C_CER	2C_EPC	1.5C_CAP	1.5C_CER	1.5C_EPC
USA	66.3% (4.9)	20.2% (8.4)	9.4% (2.1)	22.5% (6.4)	17.7% (9.9)	12.4% (5.0)	19.3% (7.7)
EU-27	28.9% (2.2)	11.5% (4.8)	4.5% (1.0)	9.0% (2.5)	10.4% (5.8)	6.9% (2.8)	9.4% (3.7)
CHINA	3.2% (0.2)	31.1% (13.0)	18.6% (4.1)	28.1% (8.0)	27.9% (15.6)	21.8% (8.8)	26.1% (10.4)
INDIA	1.0% (0.1)	9.4% (3.9)	23.0% (5.1)	6.2% (1.8)	10.2% (5.7)	16.0% (6.5)	7.8% (3.1)
ROW	0.6% (0.0)	27.8% (11.6)	44.5% (9.8)	34.2% (9.7)	33.9% (19.0)	43.0% (17.4)	37.4% (14.9)
TOTAL	100% (7.5)	100% (41.6)	100% (22.1)	100% (28.3)	100% (56.1)	100% (40.6)	100% (39.7)

The absolute costs of achieving the NDCs are around 7.5 trillion$, mostly in USA (66%) and EU-27 (29%). Mitigation costs are highest under the “capabilities” (CAP) scenario as this requires the most near-term emissions reductions: the 2C_CAP scenario cost is 45% and 80% higher than the CER and EPC criteria costs respectively. When comparing the 1.5°C scenarios, the 1.5C_CAP is around 40% greater than the cost obtained with the other criteria.

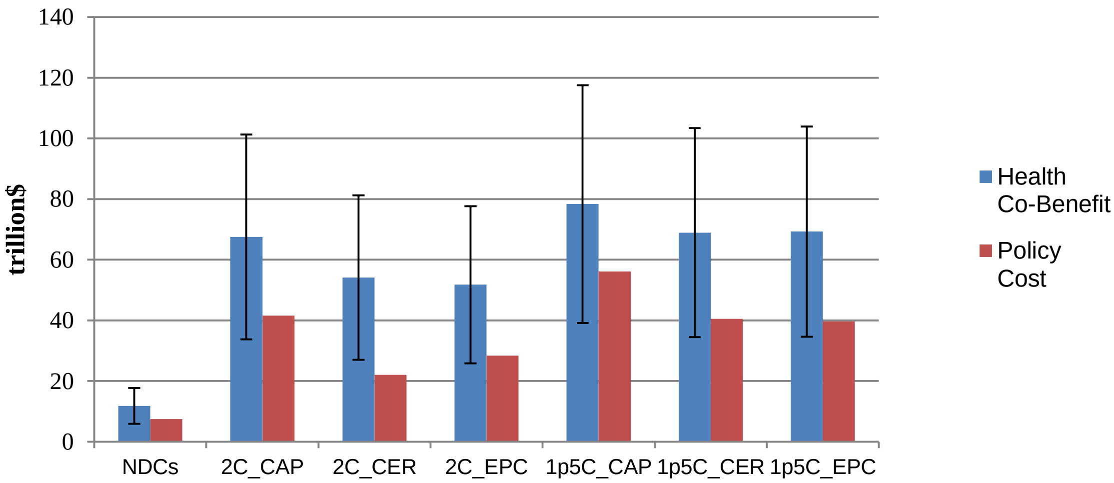
From a macroeconomic perspective, these costs are relatively low. For the 2°C target the global costs range from 0.5% to 1% of global GDP, while for the 1.5°C target the range is 1%-1.3%. Between the scenarios the lowest costs emerge under the CER or EPC scenario and the highest ones under the CAP scenario. These numbers are in line with the figures in the 5th IPCC assessment report (IPCC., 2014), where the values for different years for the 2°C scenario range from around 0 to 2%.

The results presented are based on a discount rate of 3%, which is in the middle of the range used in the literature to discount climate impacts.(Interagency Working Group, 2013; Nordhaus, 1994; Stern, 2006). As a sensitivity test, lower and higher values of 0% and 6% were also taken (see next subsection). The differences between these rates in terms of the shares of costs borne by different groups is quite small. The higher rate means future costs and benefits are given a lower value. As relatively fast growing countries in GDP and population like India and China have higher co-benefits and potentially higher costs in the future, these are given a small weight with a higher discount rate, making their share of net costs lower at a 6% rate than at a 3% rate. The reverse holds for the US. The EU is somewhere in between but the difference between the discount rates in terms of shares is only 1-2%.

Health Co-benefits vs Mitigation Costs

Figure 4.4 shows the health co-benefits and mitigation cost for each scenario. Health co-benefits are the difference between the monetized health damage of each policy scenario with respect the baseline. The figure includes an uncertainty range based on a sensitivity analysis for VSL -- the variable most influential in determining the health benefits – with the lower and the upper VSL values drawn from the literature (Holland et al., 2014).

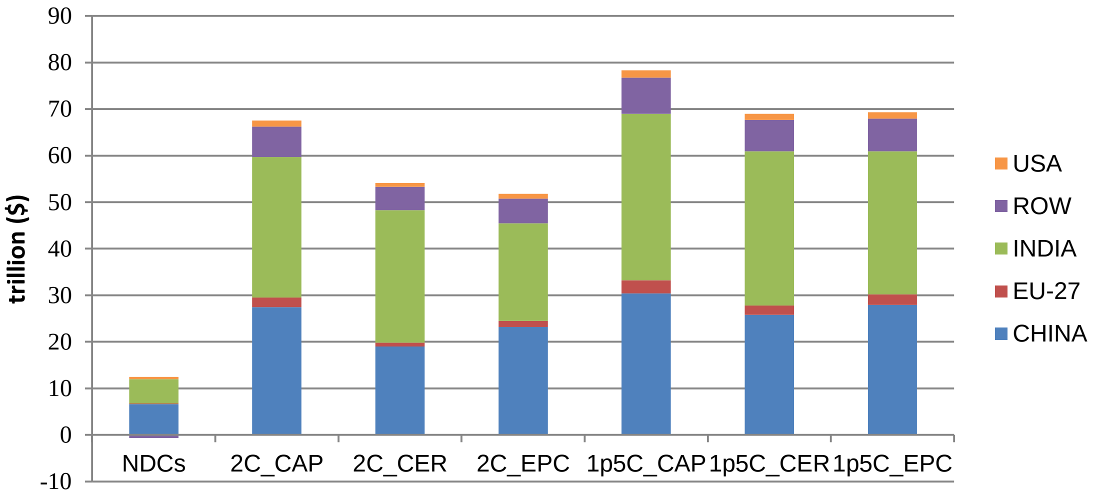
Figure 4.4:Cumulative (2020-2050) health co-benefit and mitigation cost by scenario (Trillion$). The discount rate used is 3%. The black uncertainty bars represent the range of values with lower and upper values of the VSL given in the literature.



The most notable result from this figure is that at the global level the central value of the health co-benefit is greater than the cost of achieving the mitigation target for all the scenarios. Some mitigation strategies show co-benefits that are more than double the mitigation cost. The health co-benefit to mitigation cost ratio ranges from 1.4 (1.5C_CAP) to 2.45 (2C_CER). The sensitivity analysis shows that even when taking the lower bound (of VSL), the health co-benefits are very close to the mitigation cost, covering between 70-91% of that cost. For the non-equitable 2C_CER, even the lowest estimate of the health co-benefits is higher than the mitigation cost. Note that the higher co-benefits in the CAP scenario do not outweigh the larger policy costs, which results in a lower ratio of co-benefit to cost.

Figure 4.5 show the regional distribution of these co-benefits, with the majority of the co-benefits located both in China and India. In the NDCs scenario, these countries account for 55% and 43% of the co-benefits, respectively. In the 2°C and 1.5°C mitigation scenarios, they represent similar shares.

Figure 4.5: Cumulative (2020-2050) health co-benefit per region and scenario (Trillion$). The discount rate used is 3%



In order to compare co-benefits and mitigation costs for the different mitigation pathways it is very useful to see what percentage of the additional effort of setting a more stringent target is compensated by the additional health co-benefits. This is especially important for addressing the objectives of the Paris Agreement to "pursue efforts" to reduce emissions to limit temperature increase to 1.5 °C.

Concretely it is key to analyze the policies "step by step", i.e.:

- The effect of achieving the NDCs or the 2°C target (following the different defined criteria) against the baseline (no climate policy) scenario
- The effect of achieving the extra effort of the 1.5°C instead of 2°C

Table 4.4 compares for each of the intermediate steps the marginal health co-benefits with the marginal mitigation for a range of values of the VSL. A green cell indicates that, regardless of the VSL value, the marginal health co-benefit is greater than the marginal mitigation cost. An orange colour means that whether the health co-benefits exceed the extra mitigation cost depends on the VSL value. Finally, if the cell is red, the additional health co-benefits are never sufficient to cover the additional mitigation cost.

For China and India, the mitigation costs are compensated by the co-benefits for a 2°C target, regardless the burden sharing criterion. The extra cost of going from the 2°C to the 1.5°C target is also always fully compensated for India, while for China it depends on the VSL chosen. The results in the other regions suggest that the marginal mitigation cost is often higher than the marginal co-benefit. Globally, the marginal health co-benefits outweigh the marginal mitigation cost of a 2°C target depending on the VSL value, except in the case of CER when this holds for all VSL values.

Table 4.4: Net marginal benefits by region and scenario (Trillon$).The discount rate used is 3%. The values in brackets show the range of results based on the lower and the upper bounds of the VSL.

Scenario	China	EU-27	India	ROW	USA	TOTAL
NDCs	6.36(3.06 ; 9.66)	-2.01(-2.08 ; -1.93)	5.12(2.52 ; 7.72)	-0.72(-0.38 ; -1.06)	-4.42(-4.68 ; -4.16)	4.33(-1.57 ; 10.24)
2°C						
CAP	14.49(0.77 ; 28.21)	-2.70(-3.74 ; -1.67)	26.25(11.18 ; 41.33)	-5.01(-8.29 ; -1.73)	-7.12(-7.76 ; -6.48)	25.91(-7.84 ; 59.67)
CER	14.89(5.39 ; 24.39)	-0.22(-0.60 ; 0.17)	23.40(9.16 ; 37.64)	-4.81(-7.32 ; -2.29)	-1.23(-1.65 ; -0.81)	32.03(4.97 ; 59.10)
EPC	15.22(3.62 ; 26.82)	-1.22(-1.88 ; -0.56)	19.21(8.73 ; 29.70)	-4.42(-7.05 ; -1.79)	-5.33(-5.85 ; -4.81)	23.46(-2.44 ; 49.35)
1.5°C						
CAP	0.27(-1.21 ; 1.75)	-0.27(-0.65 ; 0.12)	3.76(0.98 ; 6.55)	-6.21(-6.83 ; -5.59)	-1.21(-1.37 ; -1.06)	-3.66(-9.08 ; 1.77)
CER	2.08(-1.32 ; 5.47)	-0.60(-1.20 ; -0.01)	3.28(0.93 ; 5.63)	-5.92(-6.76 ; -5.08)	-2.47(-2.70 ; -2.24)	-3.63(-11.05 ; 3.78)
EPC	2.31(-0.05 ; 4.67)	-0.19(-0.68 ; 0.31)	8.40(3.53 ; 13.28)	-3.46(-4.32 ; -2.60)	-0.93(-1.11 ; -0.76)	6.14(-2.63 ; 14.90)

NOTE: The first rows represent the net marginal result of adopting the NDCs or the 2°C stabilization target against a no-climate-policy baseline. The last rows give the net marginal benefits of setting the "extra" 1.5°C policy against the (already stablished) 2ºC. See text for meaning of the colour scale.

In the cases where the cells are orange or red the results are not necessarily negative. Although the marginal costs are not fully compensated by the co-benefits, they still cover a portion of the marginal policy cost, in most cases a significant percentage. Finally, Table 4.5 shows a sensitivity analysis on the discount rate values. It demonstrates that the chosen value would not determine the results.

Table 4.5: Health co-benefit and policy cost per scenario and region for different discount rates (trillion $)

	Health co-benefit							Policy cost						
	No Discounted							*No Discounted*						
	NDCs	2C_CAP	2C_CER	2C_EPC	1p5C_CAP	1p5C_CER	1p5C_EPC	NDCs	2C_CAP	2C_CER	2C_EPC	1p5C_CAP	1p5C_CER	1p5C_EPC
CHINA	12.11	49.05	34.70	41.84	54.16	46.66	50.07	0.46	22.80	7.68	14.40	27.25	16.09	18.99
EU-27	0.34	3.82	1.60	2.53	5.11	3.66	4.22	3.74	8.33	1.84	4.52	10.02	5.04	6.63
INDIA	9.16	57.72	53.95	41.23	68.03	63.06	59.56	0.12	7.37	9.33	3.63	10.65	11.88	6.28
ROW	-1.02	12.10	9.37	9.81	14.26	12.40	12.88	0.10	21.70	18.50	18.31	34.78	31.96	27.95
USA	0.95	2.37	1.59	1.93	2.91	2.42	2.57	8.37	14.45	3.72	10.94	16.89	8.89	13.32
TOTAL	21.53	125.06	101.21	97.34	144.48	128.21	129.31	12.79	74.65	41.08	51.79	99.59	73.86	73.16
	DR 3%							*DR 3%*						
	NDCs	2C_CAP	2C_CER	2C_EPC	1p5C_CAP	1p5C_CER	1p5C_EPC	NDCs	2C_CAP	2C_CER	2C_EPC	1p5C_CAP	1p5C_CER	1p5C_EPC
CHINA	6.60	27.44	19.00	23.20	30.40	25.80	27.92	0.24	12.95	4.11	7.98	15.64	8.83	10.39
EU-27	0.15	2.08	0.78	1.32	2.85	1.96	2.31	2.16	4.78	0.99	2.54	5.82	2.78	3.72
INDIA	5.20	30.15	28.48	20.97	35.72	33.18	30.73	0.08	3.89	5.08	1.76	5.70	6.49	3.11
ROW	-0.67	6.56	5.03	5.26	7.80	6.71	6.98	0.05	11.57	9.84	9.68	19.02	17.44	14.86
USA	0.53	1.28	0.84	1.04	1.59	1.31	1.39	4.95	8.40	2.08	6.37	9.92	5.01	7.65
TOTAL	11.80	67.51	54.13	51.80	78.36	68.95	69.32	7.47	41.60	22.10	28.34	56.10	40.55	39.73
	DR 6%							*DR 6%*						
	NDCs	2C_CAP	2C_CER	2C_EPC	1p5C_CAP	1p5C_CER	1p5C_EPC	NDCs	2C_CAP	2C_CER	2C_EPC	1p5C_CAP	1p5C_CER	1p5C_EPC
CHINA	3.88	16.44	11.16	13.79	18.26	15.28	16.67	0.13	7.88	2.36	4.74	9.62	5.20	6.05
EU-27	0.06	1.20	0.38	0.72	1.69	1.11	1.34	1.35	2.95	0.58	1.55	3.64	1.66	2.23
INDIA	3.16	16.83	16.08	11.38	20.05	18.66	16.92	0.05	2.21	2.97	0.90	3.27	3.81	1.63
ROW	-0.47	3.79	2.88	3.01	4.55	3.87	4.03	0.02	6.61	5.61	5.49	11.17	10.22	8.42
USA	0.32	0.74	0.48	0.60	0.93	0.76	0.80	3.16	5.26	1.28	4.01	6.27	3.06	4.72
TOTAL	6.94	39.00	30.98	29.49	45.48	39.68	39.76	4.71	24.91	12.79	16.68	33.96	23.94	23.06

Discussion

This section presents some caveats that have been divided in methodological and conceptual limitations. From the methodological point of view, the GCAM model does not allow for negative CO_2 emissions as a future projected emission pathway. In this line, it should be mentioned that the criteria that have been used in this study are conceptually very diverse so, bearing in mind that it has not been possible to display a complete replication, this work allows to identify the particularities of a wide range of mitigation strategies.

Additionally, GCAM contains a highly stylized representation of air pollutant controls that has not been tuned in any way to match regional projections or expectations. Overall, because EFs in all countries decline with the same function of GDP, in general developed country emissions do not fall fast enough, and least developed country emissions fall quite fast. And, overall, the transitions are too gradual compared to history. Since the results are presented for 2050 which is medium term, these issues are not so relevant, but still will impact results.

Another modelling limitation is that population is uncertain for some countries, and projections to 2050 are even more uncertain. In the TM5-FASST model, if a given grid cell has no population in the base year no population growth takes place inside, which means that no urban land expansion can be assumed, due to the data limitations. Population growths are located in already populated grid cells. Trying to reduce the level of uncertainty, this study uses the gridded SSP2 population, provided by IIASA.

In terms of regional disaggregation, it is conceptually difficult to establish an aggregated carbon tax. Although the country-level particularities have not been analyzed in detail, the aim of this study was to see the implications at a global level. Indeed, the literature had already identified China and India as the key regions in terms of health co-benefits, regions that have been individualized in this study.

Regarding the economic assessment of the premature deaths, there are some studies that point out the moral or ethical barriers of using a GDP based value for monetizing human life (Viscusi and Aldy, 2003). This paper does not go deeply into this issue, it just takes the VSL and the associated morbidity costs as a valuable tool for comparing the health co-benefits with the policy costs.

Conclusion

Climate change and air pollution are important, interrelated problems. This chapter gives a comprehensive assessment of the global and regional implications of climate change mitigation in terms of (ambient) air pollution in the coming decades. The results show that in all the scenarios, global health co-benefits are greater than the mitigation cost of achieving the target. The health co-benefit to mitigation cost ratio ranges between 1.4 and 2.45. The staged approach (CER) is the most efficient burden sharing approach in terms of net cost.

Owing to uncertainty over VSL values, a sensitivity analysis was conducted. It shows that, even with the lower bound of the VSL the health co-benefit would cover between 70-91% of the policy costs, depending on the chosen scenario. There is one strategy (2C_CER), where, even with the lower bound VSL, the health co-benefits are greater than the costs.

To better understand which target might be favorable for each region and under what burden sharing criteria a marginal analysis was conducted, comparing the additional benefits of going from no target to an NDC based target, from no target to a 2°C target, and from a 2°C to a 1.5°C target. The results indicate in China and India the cost of setting any additional policy could be compensated just with the health benefits in most cases. Other regions could not compensate the costs by the co-benefits alone but the latter would make a valuable contribution to covering the mitigation costs – from 7% to 84% in the EU-27 and from 10% to 41% in the USA. In all cases one should not forget that attaining the 2°C target has considerable benefits from reduced climate change impacts benefits for all regions, including health benefits, and attaining a 1.5°C target has even greater climate benefits.

Chapter 5

Health co-benefits and mitigation costs as per the Paris Agreement under different technological pathways

Introduction

Air pollution is currently the 5th biggest risk to health and the top environmental risk (Forouzanfar et al., 2016; WHO 2016). Air pollution (indoor and outdoor) is the cause of 7.2 million premature deaths (WHO 2018), of which outdoor (or ambient) air pollution is responsible for 3-4 million. The most important pollutants in terms of health impacts are Particulate Matter ($PM_{2.5}$) and Ozone (O_3).

One of the main sources of air pollution is the combustion of fossil fuels, which is also the main source of greenhouse gas (GHG) emissions. This means that climate change (IPCC 2014, Cook et al. 2016) and air pollution (WHO 2016) are two interrelated environmental risks, and many polices (but not all) aimed at limiting GHG emissions reduce air pollution, generating health co-benefits. Conversely, policies focusing on reducing local pollutants can also reduce GHG emissions, although the converse can also occur.

There is a growing interest in the research and policy communities in quantifying the mitigation costs and health co-benefits of climate policy, which depend on many factors such as the global temperature target and associated emissions reduction, the temporal allocation of the carbon budget (when reductions are made), the spatial distribution of the global mitigation effort (who makes the reductions), and the technological pathway associated with the reduction of emissions (how the reductions are made). In this regard, West et al. 2013 examine the global co-benefits of GHG mitigation by comparing a baseline with an RCP4.5 scenario. They show that the monetized co-benefit exceeds the mitigation cost, and they locate the biggest effects in South and East Asia, specifically India and China. Similar results can be found in Markandya et al., 2018, where the authors demonstrate that global health co-benefits outweigh the mitigation cost for both Paris Agreement climate objectives (2°C and 1.5°C stabilization) following different "burden sharing" criteria. Baseline assumptions for air pollution control policies will also have significant effects on health co-benefits (Rao et al., 2016)

These results are also confirmed in a recent study (Vandyck et al., 2018), where a wide range of co-benefits is explored (mainly health co-benefits). It is also concluded that those co-benefits are greater than the mitigation costs, the difference being particularly large in the two regions mentioned above. A recent study (Shindell et al., 2018) focuses on the location of and variation in these co-benefits depending on the availability of negative-emission-technologies for an RCP 2.6 scenario, however the methodology used is overly simplified as shown in this chapter. Additionally ,Ou et al. 2018 finds that significant co-benefits could also occur in developed countries. Finally, there are several articles that review and classify co-benefits studies, showing a large increase on studies over recent years (Chang et al., 2017; Deng et al., 2017; Gao et al., 2018).

This study estimates global and regional health co-benefits, mitigation costs, and possible trade-offs of different technological pathways for achieving the 2°C target of the Paris Agreement. The pathways are based on the IPCC's Fifth Assessment Report (IPCC 2014, Anderson and Peters 2016) and assume different levels of development and use of some critical mitigation technologies such as bioenergy, nuclear power, and carbon capture and storage (CCS). For each scenario the emission pathways for GHGs (CO_2, CH_4, N_2O, halocarbons) and air pollutants are determined, with the associated GHG mitigation costs and health co-benefits.

It is demonstrated that co-benefits results depend significantly on baseline, scenario assumptions and the methodologies used. Effects of climate policies on air pollutant emissions, and therefore co-benefits, vary substantially by region and pollutant species. This means it is essential to capture these dynamics by developing a detailed integrated methodology that fully captures the evolution of the key technologies.

In this chapter GCAM is used to generate GHG and air pollutant emissions for each set of pathways examined. The air pollutant emissions are then used in TM5-FASST which, based on the Burnett exposure-response functions, provides $PM_{2.5}$ and O_3[34] concentration levels and estimates health impacts in terms of premature deaths. Finally, the Value of Statistical Life (VSL) approach, based on data from the OECD (OECD 2014; 2016), is used to monetize these impacts, incorporating into the analysis some additional estimates of morbidity costs. More information can be found in *methodology*. The main innovation of this exercise is the global modelling of technology based mitigation scenarios, coupled with an air quality model, in order to obtain health co-benefits under different pathways.

Scenarios

The scenarios in this study have two main components: a general socioeconomic storyline represented by the Shared Socioeconomic Pathways work (SSP) and the technological pathways represented by different technology options for achieving the 2°C target defined in the Paris Agreement. For the distribution of mitigation across regions, this study adopts a “least cost” approach with a global carbon price on energy and industrial CO_2 emissions.

In terms of socioeconomic storylines the authors chose the SSP2 narrative, considered as “the middle of the road” (see Annex IV) To implement this scenario, the SSP2 set-up scenario in the GCAM 4.3 release is used, which has since been updated recently. This will have some effect in terms of emission factors. However, the differences in global air pollutant emissions in the SSP2 case between the version used here and the updated SSP2 emission factors (Calvin et al., 2017) range from 5% (NOx) to -6% (SO_2) for 2050, as presented in Annex IV.

For technological pathways, the study follows the IPCC 5th Assessment Report (Pachauri et al., 2015), which defines pathways for achieving a 2°C target based on different levels of development or unavailability of several technology groups considered critical for achieving low emission targets (i.e. bioenergy, carbon capture and storage, and nuclear power). For example, a substantial increase in bioenergy has implications for agricultural land, which might lead to limits on the amount of cropland used for dedicated bioenergy crops. CCS technologies have not yet been implemented at a large scale, and some implementation projects have experienced significant difficulties, so it is useful to consider scenarios where CCS is not widely deployed. The scenarios considered here are summarized in Table 5.1.

All of the GCAM scenarios, with or without a climate policy, have implicit emission controls for different air pollutants. This implies that non-GHG emissions would also decrease over time, in the baseline scenario. Indeed, as noted in the documentation, the applied GCAM implementation of the SSP scenarios incorporates region-, sector-, and fuel-specific pollutant emission factor pathways (Rao et al., 2017).

[34] The CH_4 concentrations and their impact on ozone are estimated in TM5-FASST based on (Fiore et al., 2009)

Table 5.1: Scenarios. All the scenarios (except the baseline) are expected to achieve the 2℃ temperature stabilization target of the Paris Agreement. However, each presents individual features in terms of technological development.

Scenario	Description
Baseline	There is no long term climate target established. This scenario includes region, sector, and fuel-specific pollutant emission factor pathways, based on (Rao et al., 2017).
All available	There is a 2°C temperature target for 2100, with no explicit technological limit. GCAM model, based on prices and preferences determines the energy mix following a logit competition.
Bioenergy limitation	There is a 2°C temperature target for 2100, with a global limitation on bioenergy consumption of 100 EJ. Bioenergy includes purpose grown biomass and crop waste and residues. Biogas is implicitly included in the limitation.
Low CCS	There is a 2°C temperature target for 2100, but the availability and the cost of CCS technologies are limited by multiplying the CCS capital costs from the baseline scenario (used by default in the GCAM model) by a factor of 10 (Calvin et al., 2017).
Nuclear Phase-out	There is a 2°C temperature target for 2100, with a limitation in nuclear energy. There is a gradual phase-out of current nuclear power plants, according to their lifetime. There is no additional installation of new plants.

Regarding the comparison, the outputs of the 2°C[35] scenarios have been compared with the same reference for simplicity. However, it has been tested if the results of the reference would be modified due to technological constraints (bioenergy or nuclear limitations). To establish a limit of 100 EJ on bioenergy (with no climate policy) does not affect the results up to 2050, as it is only exceeded from 2090 to 2100 in the reference scenario, when the bioenergy consumption accounts for 105 EJ. Similarly, the phase-out of nuclear power, without long-term climate targets, has no significant effect on the reference air pollutant emission pathways, as they do not significantly differ from the reference used (“no constrained”) (<2% of variation in all of the species). Carbon capture and storage (CCS) does not come into a reference scenario with no carbon price applied, so these assumptions have no impact on the reference scenario.

[35] The temperature targets (and results) are calculated from the MAGICC 5.3 model, a reduced-form climate model included in the GCAM version used. For more details, see: Wigley, 2008, and Smith and Bond, 2014 for the representation of BC and OC forcing.

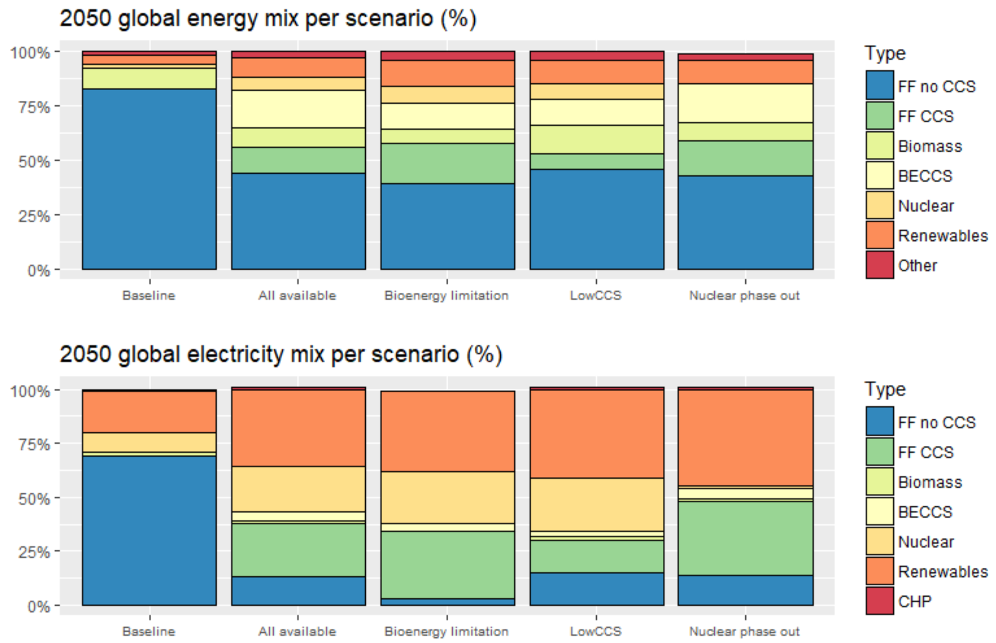
Results

Energy and electricity system

This subsection presents the impacts of the different technological pathways in terms of the energy and electricity mix, emission pathways, $PM_{2.5}$ concentrations, premature deaths, mitigation costs, and health co-benefits for 18 World regions up to 2050.

Each technological pathway results in a different structure of the energy system. Figure 5.1 summarizes the energy and electricity mix for 2050 under the different technological assumptions:

Figure 5.1: 2050 global energy and electricity mix per scenario (%)



In the baseline scenario, fossil fuels (without CCS) account for 83% of the energy mix in 2050, followed by bioenergy (no CCS), renewable energy and nuclear power, which account for 9%, 4% and 2% of the mix respectively in that scenario. A similar structure can be seen in the electricity system, which accounts for between 24 and 36% of final energy consumption. There, fossil fuels with no carbon capture and storage account for around 70%, while other technologies such as renewables (19%), nuclear (9%), and bioenergy (2%) play a smaller part.

In the 2°C scenarios, the global energy demand decreases from -6% to -30% depending on the scenario and period. In terms of technological changes, the main difference is in the use of fossil fuels (FF), with and without carbon capture and storage (CCS), with the share of those FF being reduced drastically, in the range of 38% to 46%, depending on the technological pathway.

Global expansion of renewable energy sources, which demonstrate their importance for achieving the temperature target in all the scenarios presented. Focusing on the electricity mix, they more than double their share from 19% (baseline) to 44% in the nuclear phase-out scenario by 2050. The largest increments occur in wind and solar technologies, increasing from 6 and 3% of total electricity in the baseline to 17-23% and 10-12% in the policy scenarios, respectively. Additionally, total electricity consumption significantly increases in the policy scenarios (up to 20%, when bioenergy is limited), which makes the share of renewables relatively even more important.

As expected, the development of other technologies such as bioenergy, CCS, and nuclear power is directly related to the scenario analyzed, but they are always significantly more important than in the baseline scenario. Moreover, depending on the technological pathway, they could account for large proportions of the total energy mix: CCS technologies around 20% in the bio-limited scenario, biomass (no CCS) up to 13% in the Low CCS scenario, and nuclear power around 8% in the scenario with the bioenergy limitation.

GHG and air pollutant emissions

These variations consequently result in different emission pathways for each scenario, since the emission factors for pollutants are not the same across the technologies. Consequently, even though the stabilization target is similar, there are differences in emission levels. Figure 5.2. shows some of these differences in the cumulative (2020 - 2050) CO_2 reductions in each of the regions defined and Figure 5.3 shows the projections for the main air pollutants.

Figure 5.2: Share of cumulative reduction in fossil CO_2 (2020 – 2050) emissions per scenario

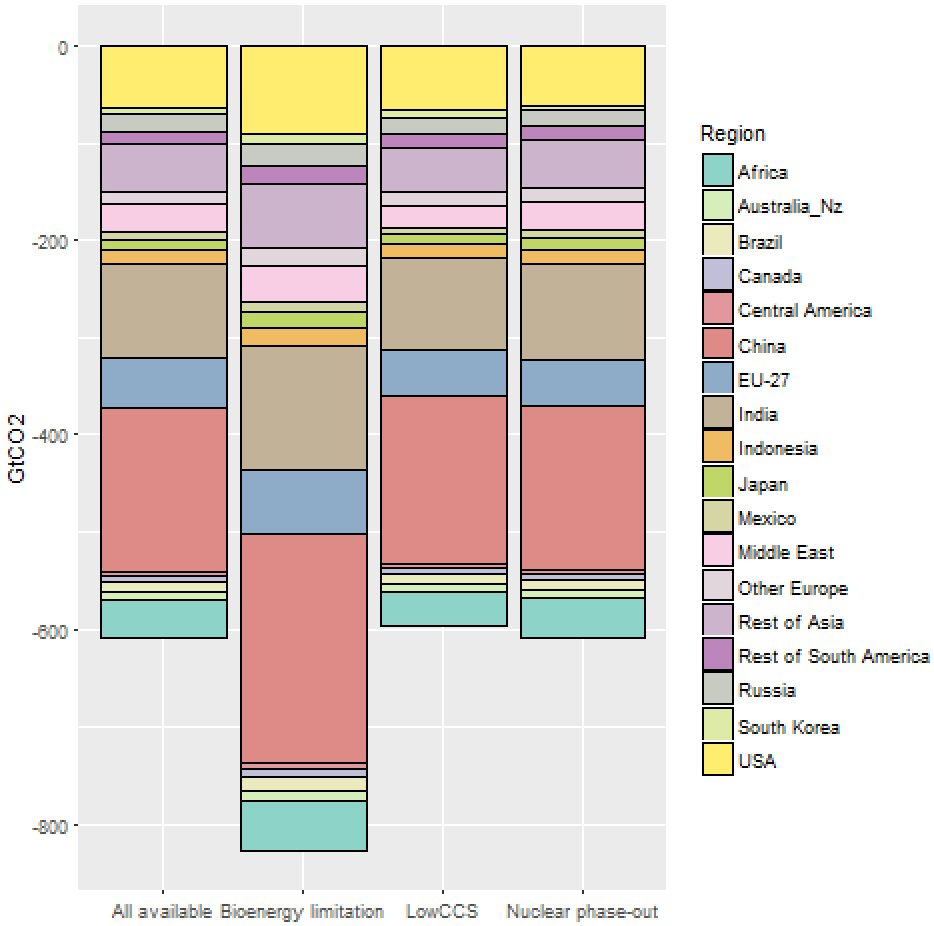
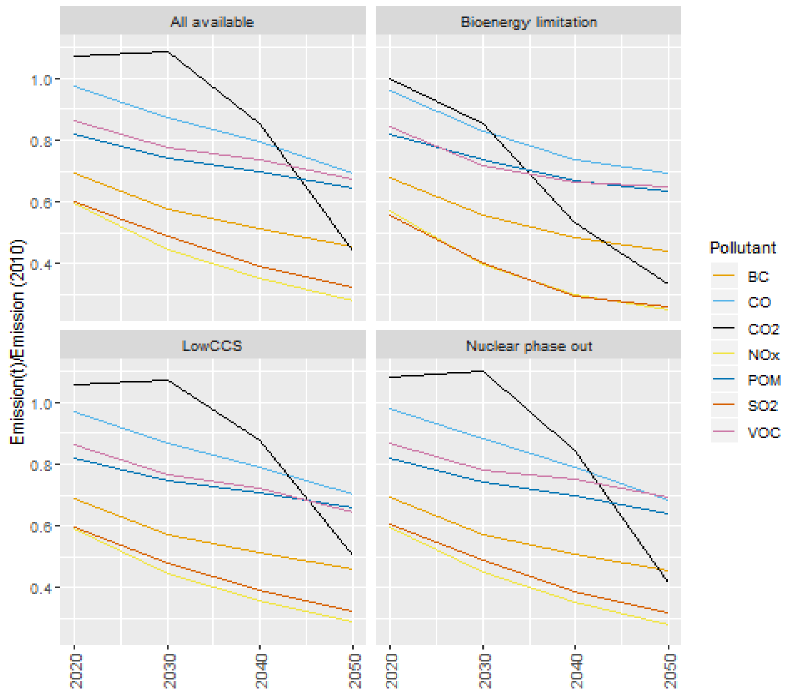


Figure 5.3: Projection for main air pollutants per period and scenario. Index=2010



These results first show that the time path of CO_2 emissions can be quite different from one scenario to another. When bioenergy is limited, emissions decrease more rapidly, as the possibility of having net negative emissions in future periods will depend entirely on the availability of biomass-related technologies. So, while in the other policy scenarios cumulative CO_2 emissions decrease by around 40% by 2050 compared to the baseline, in the Bioenergy limitation scenario the reduction is 55% by 2050, i.e. an extra 23%.

Regarding the spatial distribution, Figure 5.2 shows that the biggest reduction in cumulative emissions is found in China (around 28% of the total reduction), followed by India (15-16%) and the USA (10-11%). To achieve the target, the model follows a “least cost” approach, so there are larger reductions in those regions where it is more feasible and cost effective to decrease emissions. That is why regions such as China and India show the largest reductions.

It is important to note that, while the stabilization targets are set for 2100, we are focusing on results in 2050 (consistent with our focus on air pollutant co-benefits, and the co-benefits literature in general). While all the scenarios achieve the 2°C stabilization target set by 2100, cumulative emissions (of different pollutant species) up to 2050 differ. Global temperature change in the policy scenarios is 2°C in all four scenarios, which is by design. The pathways are very similar except for the bioenergy limitation scenario, wherein temperature change has a lower overshoot due to larger near-term CO_2 reductions as described below. In order to reflect that divergences, the following figures present the temperature increase and the CO_2 emissions pathways and up to 2050.

Figure 5.4: CO_2 emission pathways per scenario ($GtCO_2$)

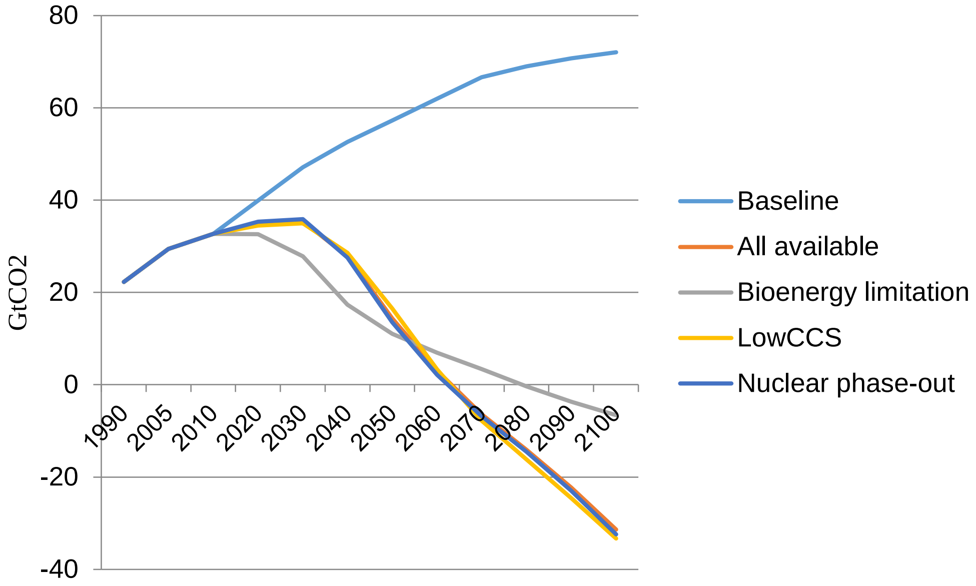
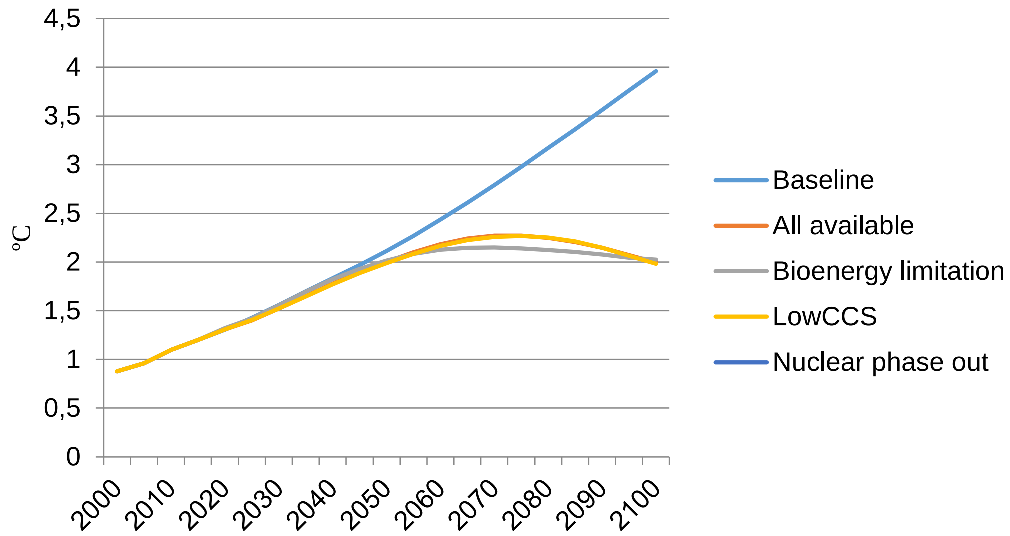
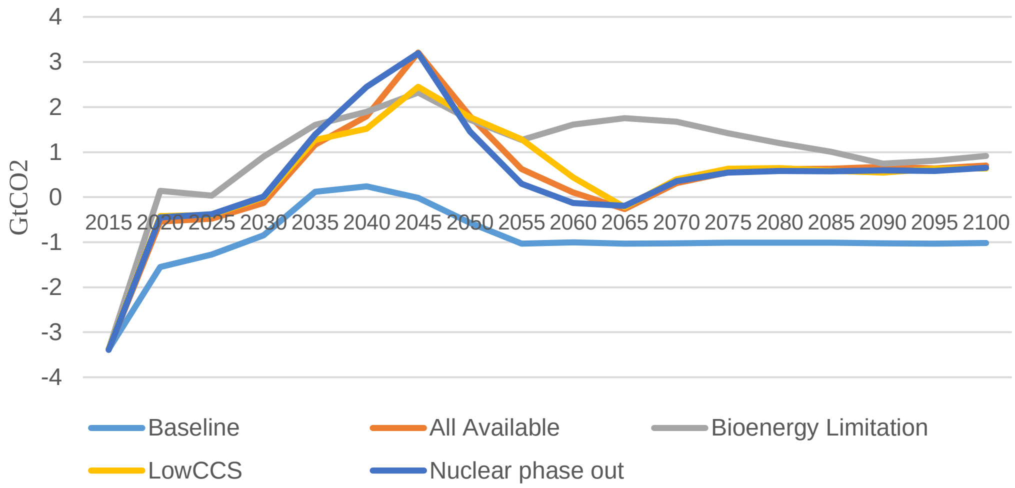


Figure 5.5: Global temperature change per scenario and period (°C)



When bioenergy is limited, CO_2 reductions need to be accomplished over a shorter time horizon since net negative emissions, through bioenergy with CCS, is not available as an offset. Consequently, in the longer term (from 2060 to 2100) the CO_2 emissions decrease for achieving the 2°C temperature target is smaller. This is consistent with the results presented in the main text, where this scenario, up to 2050, has the largest CO_2 emission reduction. Another effect of this limitation of bioenergy can be seen on the CO_2 land use change (hereinafter LUC) emissions, as presented in Figure 5.6. Note that LUC CO_2 emissions impact CO_2 concentrations in GCAM and, therefore, also play a role in the pathway required to meet a temperature target.

Figure 5.6: CO_2 and use change (LUC) emissions per period and scenario($GtCO_2$)



In the short term, (up to 2030), the bioenergy limited scenario shows larger CO_2 LUC emissions, since the total biomass consumption is higher than in the other mitigation (and baseline) scenarios. However, when the biomass limit (set in the restriction) is achieved, those LUC emissions would decrease compared to the other 2℃ scenarios, where the biomass consumption increases exponentially to achieve the target. In the long term, which is not the scope of this study, the higher direct use of crops for energy (such as corn or sugar) in the bio-limited scenario requires a significant amount of land due to its relative inefficiency. For that reason, the LUC emissions are larger in the second half of the century, despite the lower use of biomass.

As explained in the *methodology* subsection, the gases tracked are the main precursors for the formation of both $PM_{2.5}$ and O_3 (Klimont et al., 2017; Turner et al., 2016). Thus, their spatial distribution is directly driven by regional emissions from the GCAM model. Since $PM_{2.5}$ and O_3 are the most hazardous elements in terms of damage to health, figures below compares worldwide concentration levels in 2050 for mitigation scenarios relative to the baseline.

Figure 5.7: Difference in $PM_{2.5}$ concentrations between baseline and policy scenarios for 2050 (log(µg/m3))

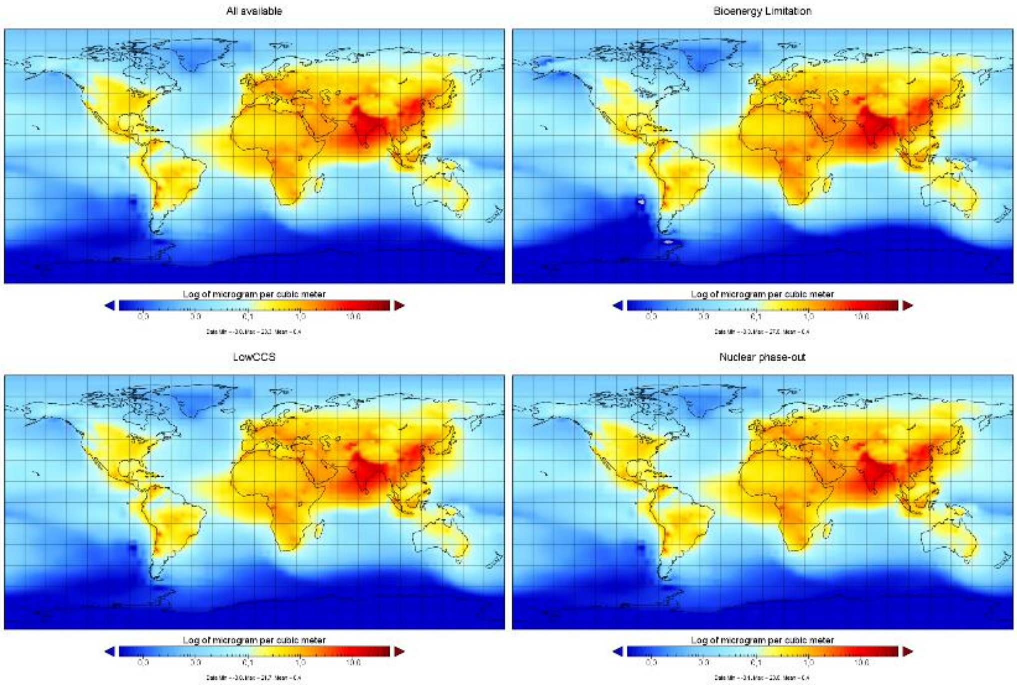


Figure 5.8:Difference in O_3 concentrations between baseline and policy scenarios for 2050 (log ppb)

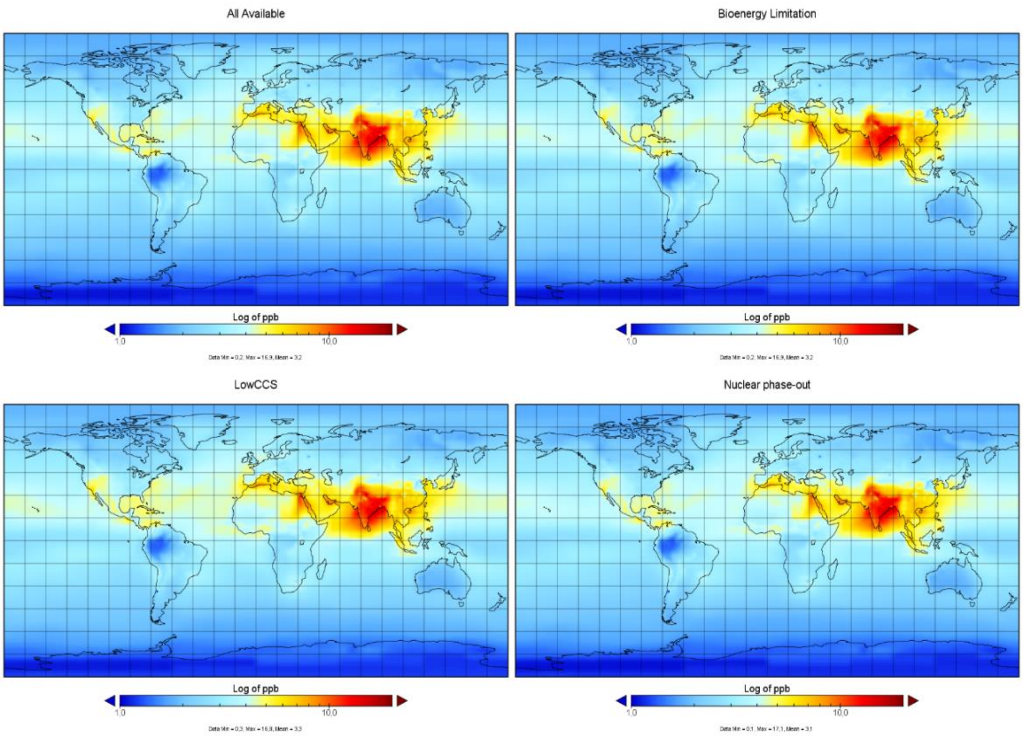


Figure 5.7 shows that the largest reductions are achieved in South and East Asia, more concretely in India and China. As mentioned, the "least cost" approach results in these regions showing the largest reductions.

Premature deaths

Once the regional concentration levels are calculated, they are converted into health impacts in terms of premature deaths using the TM5-FASST model. Figure 5.9 shows the air-pollution driven premature deaths per scenario for different time horizons. In the same line, Figure 5.10 and Figure 5.11 present some additional results such as cumulative (2020-2050) deaths and their spatial distribution in 2050 (closely related to the $PM_{2.5}$ concentration maps)

Figure 5.9: Worldwide outdoor air pollution driven premature deaths per scenario and period (million)

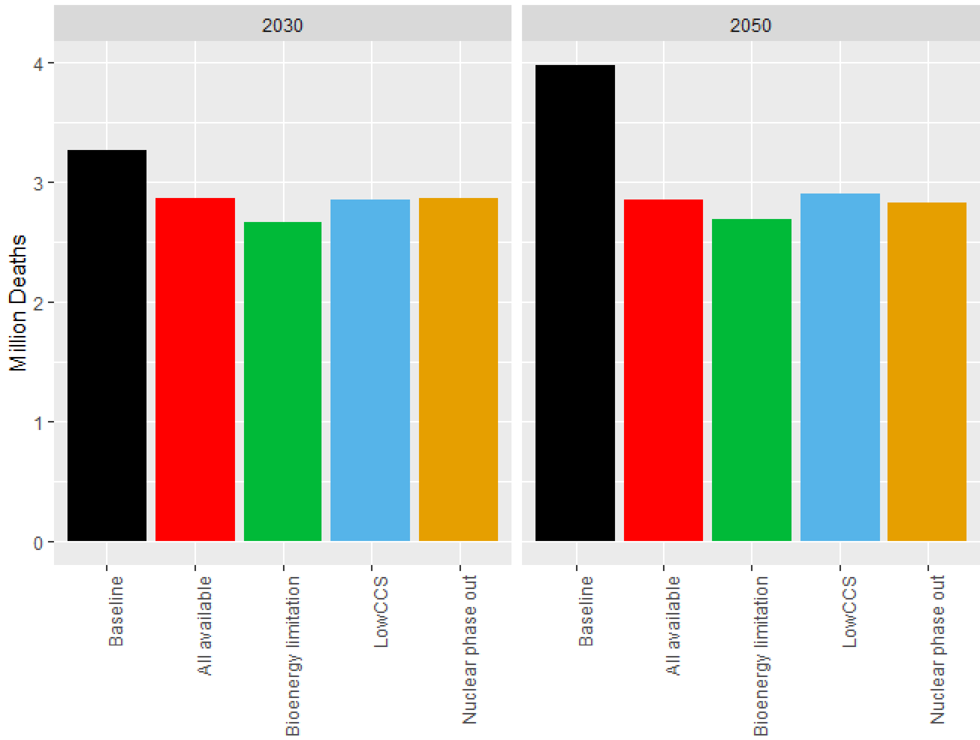


Figure 5.10: Difference in premature deaths between baseline and policy scenarios for 2050 (log of deaths)

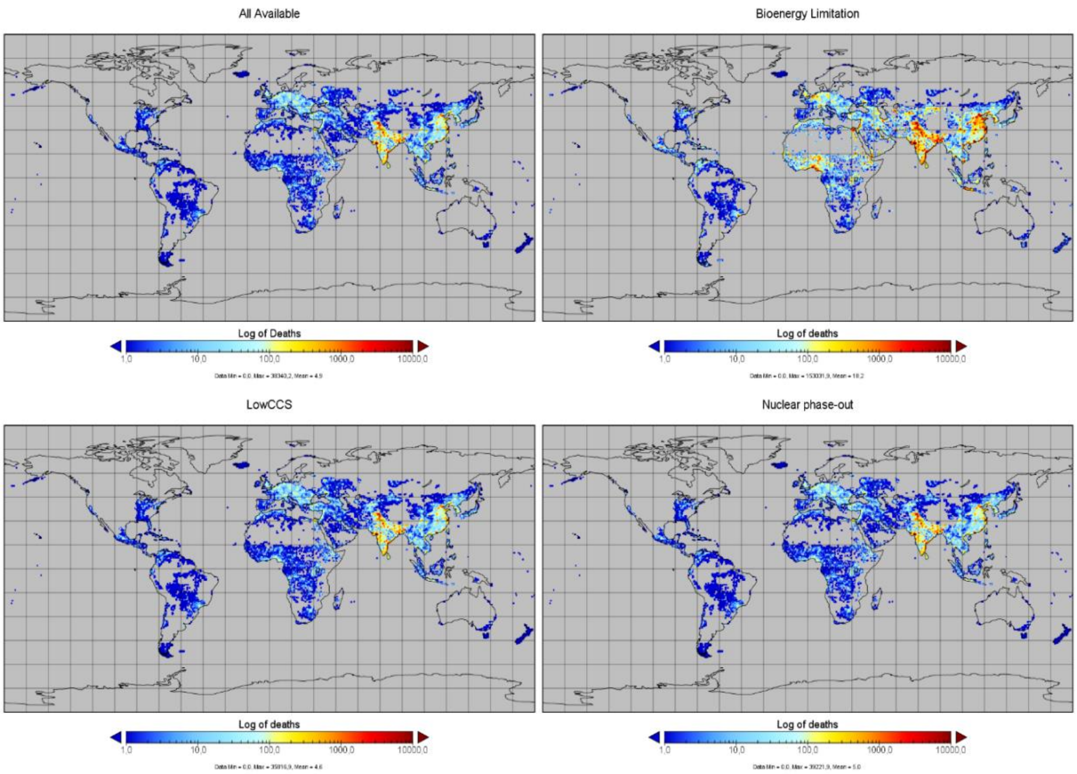


Figure 5.11: Cumulative (2020-2050) premature deaths per scenario (million deaths)

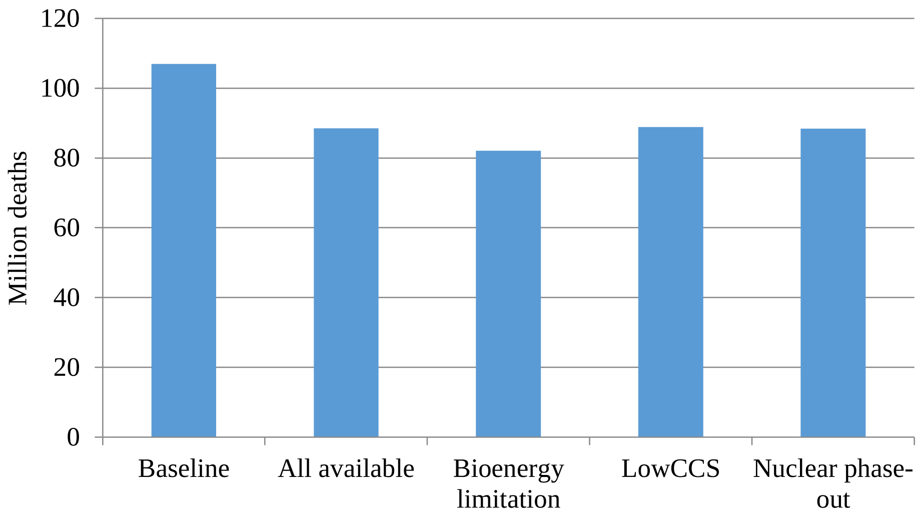


Figure 5.10 shows the premature deaths in the medium (2030) and long term (2050). It is clear that when no climate policy is set, premature deaths increase continuously. Specifically, they reach almost 4 million in 2050, compared to 3.2 million in 2030. These figures are driven by a combination of changing air pollutant concentrations and generally increasing population levels. The projected premature deaths decrease and stabilize across the 2°C scenarios, with the values determined by the technological development pathway chosen: compared to the baseline,

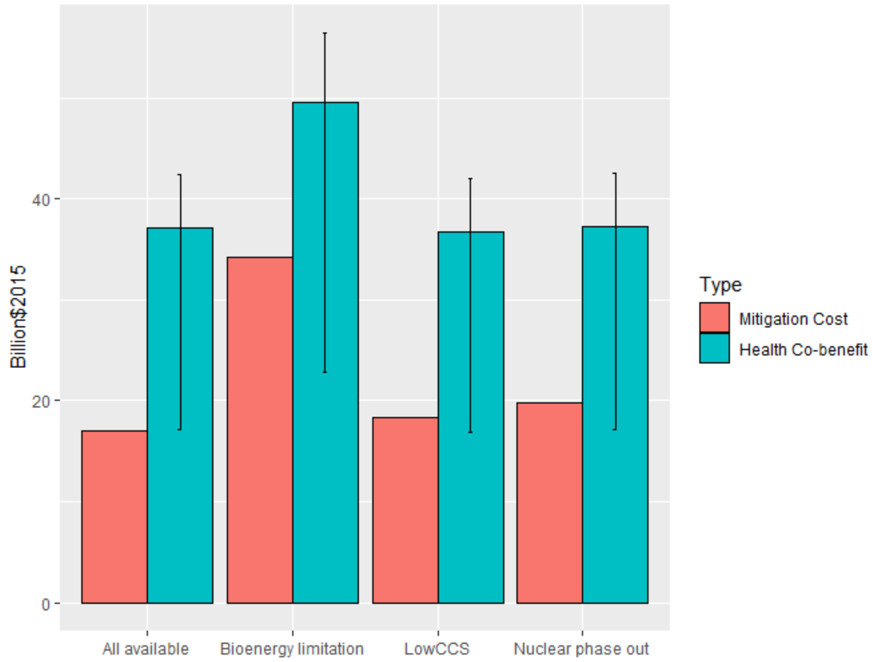
these reductions amount to 12-19%, and 27-32% in the medium and long term respectively, depending on the scenario.

In cumulative terms (2020-2050), mortality falls by around 16-17% when a stabilization target is applied. Moreover, when a bioenergy limitation is established the effect increases to 23% as the GHG and air pollutant emission reductions are larger than in the other 2°C scenarios. As expected, taking into consideration the spatial concentration levels, the highest numbers of avoided deaths are in India and China.

Health Co-benefits vs Mitigation Costs

Figure 5.12 shows cumulative[36] (2020-2050) health co-benefits per scenario, using a 3% discount rate.

Figure 5.12: Cumulative (2020 - 2050) health co-benefits and mitigation costs per scenario (US$ trillion). The uncertainty bars represent the consistent lower and upper bounds, combining Zcf and VSL values. The DR used is 3%



Two key messages can be derived from this figure: First, globally, health co-benefits outweigh mitigation costs in almost all cases, irrespective of what technological developments, limitations, or VSL values are assumed.

Second, as expected, there are significant divergences between the different technological pathways, which is in line with the aforementioned literature (Ou et al., 2018; Shindell et al., 2018). The Bioenergy Limitation Scenario has the highest co-benefit, as its net present value (NPV) is US$ 50 trillion, while the co-benefits in other mitigation scenarios are in the range of US$ 36-37 trillion. However, there is also a significant difference in the cost side: in the scenario

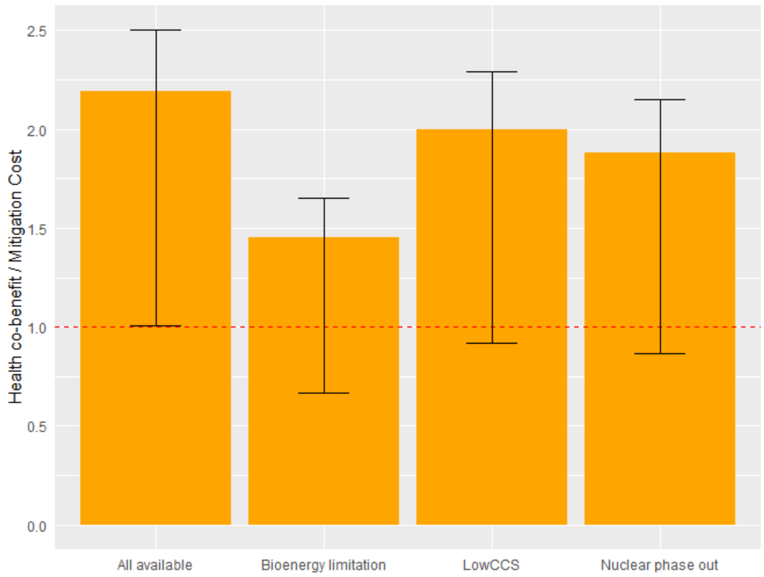
[36] To show cumulative results (2020 – 2050), to provide an aggregate measure of results over the time frame considered, a discount rate of 3% is used, which is in the middle of the range used in the literature to discount climate impacts (Nordhaus, 1994; Stern, 2006). The sensitivity analysis performed in the previous chapter has demonstrated that changing this rate does not significantly change the main conclusions.

with the bioenergy limitation the cost is US$ 34 trillion, almost double the costs of the other mitigation scenarios (US$ 16-20 trillion).

In order to address the uncertainty in these calculations, a sensitivity analysis has been performed to assess the extent to which results depend on the two key inputs of the analysis: theoretical minimum concentration below which there is considered to be no health impact (hereinafter Zcf, see below) for $PM_{2.5}$, and the VSL.

In the default TM5-FASST version, for $PM_{2.5}$ exposures, Zcf for each cause of death ranges from 6.79 µg/m3 (for ALRI) to 8.8 µg/m3 (for stroke), consistent with the literature[37]. On the economic side, health co-benefits have also been calculated using different values of statistical life. By default, the study uses the median value of the range of VSL, but for the sensitivity analysis the VSL lower and upper bounds (OECD) are used. By combining these elements (Zcf and VSL), the lowest co-benefits[38] are found using the lowest VSL and the highest Zcf (the default TM5-FASST values[39]). By contrast, the highest co-benefits are defined by combining the upper bound of the VSL and the lowest Zcf (0 µg/m3[40]). The cost-effectiveness of each scenario may be of interest for policy design. It is calculated as the health co-benefit divided by the cost, and can be seen in Figure 5.13:

Figure 5.13: Ratio of health co-benefit to mitigation cost per scenario (health co-benefit/mitigation cost). The uncertainty bars represent the consistent lower and upper bounds, combining Zcf and VSL values. The DR used is 3%



[37] For example, Burnett et al. 2014 define the Zcf as a uniform distribution: Zcf ~U[5.8, 8.8](Silva, 2015). Similarly, (Lelieveld et al., 2015) set the Zcf at 7.3 µg/m3 for all causes of death. However, these values can be considered relatively high compared to the new Global Burden of Disease study (Forouzanfar et al., 2016), which defines the lower bound (2.4 µg/m3), median (4.15 µg/m3), and upper bound (5.9 µg/m3) Zcf values.

[38] Even by applying the lowest VSL and the highest Zcf, the co-benefits exceed a significant amount of the global mitigation costs (from 67% to 100% depending on the scenario).

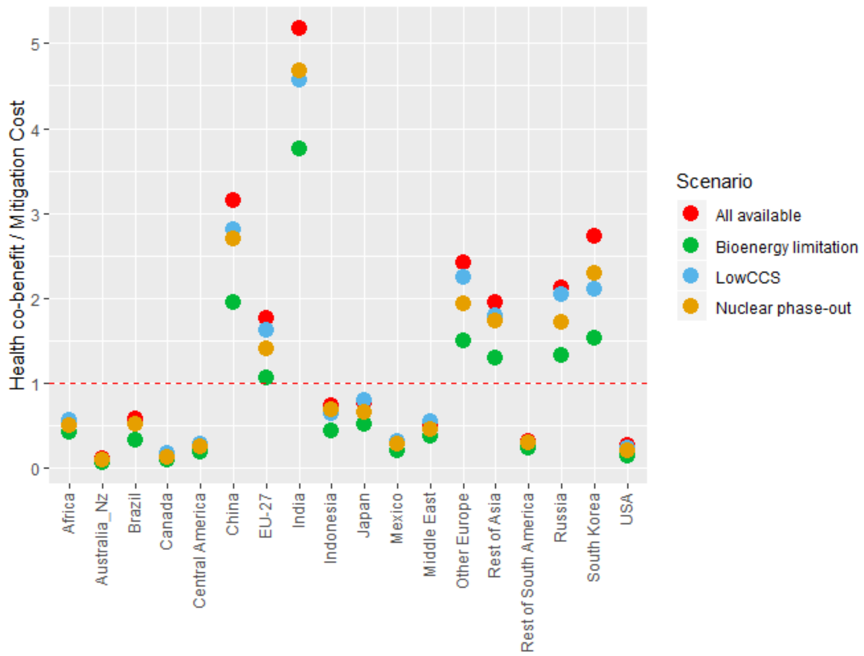
[39] These values are 7.58µg/m3 for COPD, 6.91 µg/m3 for LC, 6.79 µg/m3 for ALRI, 8.80 µg/m3 for Stroke and 6.86 µg/m3 for IHD

[40] Some studies suggest that significant damage could be obtained from exposures that are under the current GBD thresholds (Di et al., 2017)

Health co-benefits outweigh mitigation costs by very different proportions depending on the technological development, ranging from 1.45 (Bioenergy limitation) to around 2.19 (all available scenario). With no limitation on any particular technology, the "All available" scenario, global health co-benefits would be twice as great as the cost of the policy for achieving the 2°C target. As shown in Figure 5.12 , even though the bioenergy limited scenario presents higher co-benefits, it has also significantly larger mitigation cost.

The regional disaggregation of the costs and co-benefits are also examined, with Figure 5.14 showing the co-benefit to cost ratio for 18 regions. Regarding burden sharing, a single global CO_2 market has been applied, so the reductions are undertaken where they are cheapest.

Figure 5.14: Ratio of health co-benefit to mitigation cost per scenario (health co-benefit/mitigation cost). The DR used is 3%



The figure shows that there are major differences around the world. Even though values are different between scenarios, some regional patterns can be identified. First, there are some regions where the co-benefits are significantly greater than the mitigation costs, particularly for India and China. These two countries have ratios of 3.75-5.17 and 1.95-3.15 respectively. Between them they account for 33-37% and 37-38% of global co-benefits while bearing around 14 and 24% of global mitigation costs, respectively. Factors such as development stage and high population densities mean that all the mitigation strategies considered produce high co-benefits in these regions.

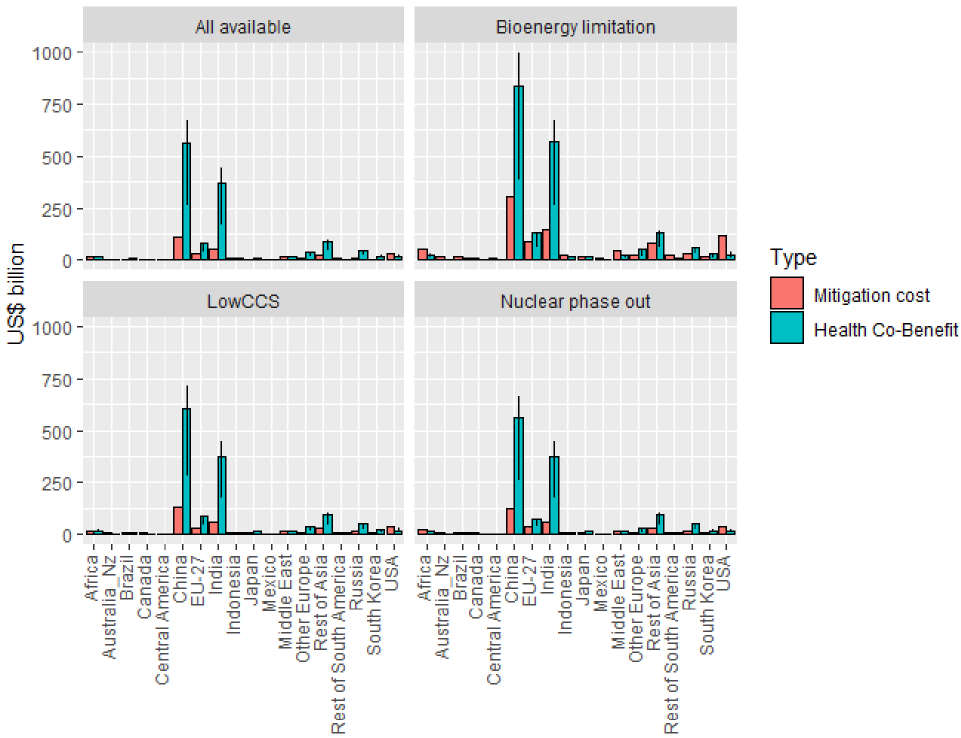
Other regions such as Europe[41], Russia or Middle East, also have health co-benefits that are larger than mitigation costs, even though they have different national characteristics. These results can be explained by the ease (and relative cheapness) with which they can implement

[41] Although the results obtained are not similar to those of the previous chapter, in this study there are no distributional criteria, so this result is consistent with the "least cost" solving strategy applied.

low carbon strategies, present-day air pollution levels, and the assumed improvements in pollution controls in the baseline scenario.

Finally, there are other countries and regions where health co-benefits are not larger than mitigation costs, even though co-benefits sometimes are still relatively large. These regions include Canada, Australia, South America and the USA, where there are low population densities and, in some cases, where significant air pollution policies have already been implemented. However, health co-benefits need to be taken into consideration for policy design in these regions as well. In addition to the cumulative results shown above provide, Figure 5.15 shows the mid-term (2030) co-benefits and costs by region.

Figure 5.15: Mid-term (2030) health co-benefits and mitigation costs per region and scenario (US$ Billion). The uncertainty bars represent the consistent lower and upper bounds, combining Zcf and VSL values.



Globally, cost-effectiveness increases and the ratios of health co-benefits to mitigation costs are higher in 2030 than in 2050, ranging from 1.92 (bioenergy limitation) to 3.83 (all available) in 2030. This result demonstrates that near-term implementation of comprehensive GHG mitigation strategies would result in benefits in terms of pollution and human health. Although China and India have similar cumulative health co-benefits, China has larger co-benefits in 2030, while India has the greatest co-benefits in 2050. The following tables provide detailed information on the cumulative health co-benefits, mitigation costs, and ratios per region and scenario.

Table 5.2: Health Co-benefit and Mitigation cost per region, period and Scenario (US$ Million)

	2020							
	Health Co-benefit				Mitigation Cost			
	All available	**Bioenergy limitation**	**Low CCS**	**Nuclear phase out**	**All available**	**Bioenergy limitation**	**Low CCS**	**Nuclear phase out**
Africa	6194	8573	6589	5951	3325	8226	4072	3782
Australia_Nz	354	495	379	376	1060	2678	1309	1211
Brazil	3860	5078	4036	3997	1346	3007	1597	1499
Canada	680	870	714	612	793	2061	972	995
Central America	415	593	446	411	410	1013	503	466
China	221302	294465	234753	219050	32903	74598	39384	38809
EU-27	45049	55998	47025	35752	7651	20115	9391	9350
Other Europe	20488	24842	21362	16993	2454	6202	2989	2894
India	85639	121806	92089	84597	11811	27629	14277	13720
Indonesia	2897	4051	3152	3022	1683	4019	2046	1911
Japan	9370	13176	10161	9491	1928	4741	2351	2184
Mexico	911	1355	973	910	771	1969	950	886
Middle East	5343	7912	5861	5179	2383	6293	2960	2739
Rest of Asia	40481	54444	43223	40689	6391	16202	7838	7304
Rest of South America	1732	2336	1871	1828	1696	4313	2075	1925
Russia	41723	51405	43852	40246	3275	8048	3997	3774
South Korea	14055	18600	14943	14057	1270	3479	1567	1563
USA	9885	12945	10479	8617	7533	21185	9268	9758
TOTAL	510377	678943	541907	491779	88683	215778	107545	104771

	2030							
	Health Co-benefit				Mitigation Cost			
	All available	**Bioenergy limitation**	**LowCCS**	**Nuclear phase out**	**All available**	**Bioenergy limitation**	**Low CCS**	**Nuclear phase out**
Africa	16798	26075	16924	16650	16991	52633	18362	19500
Australia_Nz	880	1218	936	912	3852	13782	4888	4500
Brazil	6985	9497	7384	7198	5717	17440	6932	6555
Canada	1291	1827	1358	1213	3362	11368	4146	4333
Central America	1151	1784	1237	1217	2041	6261	2375	2355
China	566331	838836	601953	558062	108551	305035	128503	123466
EU-27	84331	129491	86925	74877	27632	87019	30981	33433
Other Europe	36165	55790	37989	32556	8544	24577	9910	9986
India	367263	569784	371415	370706	53003	143858	59053	60833
Indonesia	9654	13855	9905	9991	8065	22275	9028	9201
Japan	12712	18865	13647	12602	5566	17501	6649	6376
Mexico	2426	3697	2566	2531	3334	10817	4035	3855
Middle East	14694	23871	14451	14801	13217	43215	13974	15331
Rest of Asia	91766	133710	94947	92948	26852	78033	30779	31191
Rest of South America	4391	6324	4700	4546	7280	22474	8880	8404
Russia	48578	62628	50667	47566	10868	29598	12959	12925
South Korea	19797	28298	21371	18168	3984	13213	5071	4370
USA	16762	26246	17910	15397	31033	118481	39822	37983
TOTAL	1301974	1951796	1356285	1281942	339889	1017581	396346	394598

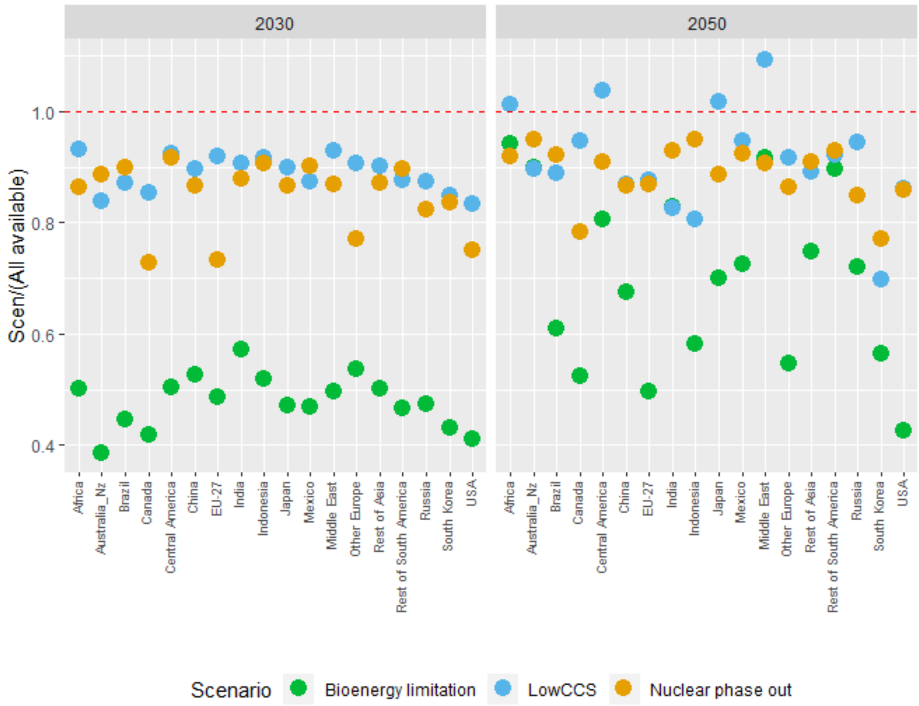
	2050							
	Health Co-benefit				Mitigation Cost			
	All available	**Bioenergy limitation**	**Low CCS**	**Nuclear phase out**	**All available**	**Bioenergy limitation**	**Low CCS**	**Nuclear phase out**
Africa	97736	116082	96404	98588	265147	334293	258042	290897
Australia_Nz	2946	3162	2949	3042	44852	53484	50125	48798
Brazil	21235	20161	20356	22072	73974	115012	79761	83477
Canada	4360	3063	4166	4423	42485	57006	42851	55074
Central America	4586	5536	4579	4724	29766	44573	28677	33701
China	1513062	1396389	1452189	1531662	825708	1129932	912130	964855
EU-27	303165	209267	278592	316596	256292	356577	268522	308193
Other Europe	97212	79222	90402	100283	74682	111307	75821	89049
India	1882350	2402301	1794067	1921977	482296	743345	555810	529950
Indonesia	35165	40071	33747	36372	73032	142780	86958	79581
Japan	22954	20552	21634	23506	84295	107654	78022	97358
Mexico	11350	10653	10572	11841	62629	80882	61658	70598
Middle East	57798	67995	55402	59170	210878	270732	184755	238342
Rest of Asia	311412	364698	298010	317763	270809	424498	290912	303953
Rest of South America	16566	20425	16607	17199	90001	123831	97894	100432
Russia	75171	78259	73602	77163	98044	141425	101769	118456
South Korea	44667	39792	42559	43117	31256	49302	42731	39096
USA	71782	40773	65793	74347	439427	584744	467073	529572
TOTAL	4573515	4918399	4361629	4663845	3455573	4871377	3683513	3981381

Table 5.3: Cumulative (2020-2050) Health co-benefit and Mitigation cost (US$ trillion)

	Health co-benefit				Mitigation Cost			
	All available	Bioenergy limitation	Low CCS	Nuclear phase out	All availabl e	Bioenergy limitation	LowCCS	Nuclear phase out
Africa	0.62	0.86	0.62	0.62	1.11	2.01	1.09	1.25
Australia_Nz	0.02	0.03	0.03	0.03	0.22	0.42	0.26	0.25
Brazil	0.19	0.23	0.19	0.19	0.32	0.68	0.36	0.37
Canada	0.04	0.04	0.04	0.04	0.20	0.39	0.21	0.26
Central America	0.04	0.05	0.04	0.04	0.13	0.26	0.12	0.14
China	14.15	18.36	14.31	14.06	4.50	9.37	5.09	5.21
EU-27	2.42	2.84	2.36	2.38	1.38	2.68	1.45	1.69
Other Europe	0.94	1.18	0.93	0.92	0.39	0.78	0.41	0.47
India	12.88	18.41	12.40	13.11	2.49	4.91	2.71	2.80
Indonesia	0.28	0.37	0.28	0.29	0.38	0.84	0.42	0.42
Japan	0.28	0.38	0.29	0.28	0.37	0.72	0.36	0.43
Mexico	0.08	0.10	0.08	0.08	0.24	0.47	0.24	0.28
Middle East	0.44	0.63	0.43	0.45	0.86	1.67	0.78	1.00
Rest of Asia	2.59	3.51	2.56	2.64	1.32	2.69	1.43	1.52
Rest of South America	0.13	0.18	0.13	0.14	0.40	0.77	0.44	0.46
Russia	1.05	1.29	1.07	1.04	0.49	0.97	0.52	0.60
South Korea	0.47	0.62	0.49	0.44	0.17	0.40	0.23	0.19
USA	0.53	0.58	0.52	0.52	2.00	4.13	2.25	2.45
TOTAL	37.16	49.63	36.75	37.26	16.96	34.17	18.38	19.82

In order to see the regional cost-effectiveness (ratio health co-benefit to mitigation cost) of each scenario, Figure 5.16 compares the ratio of each scenario with the "All available" pathway for each period. It shows that the bioenergy limited scenario is the less cost-effective in most of the cases, although there are some regions where the divergences between scenarios decrease significantly in the long term (2050). For the "LowCCS" and "Nuclear phase out" scenarios, the cost-effectiveness is closer to the "All available" scenario, but there are some interesting differences. First, there are some regions (Canada, Europe and USA) that are much less cost-effective when nuclear energy is phased out. This effect is larger in the mid-term. The reason is that those regions already have a significant amount of non-CO_2 emitting nuclear power installed (which is gradually phased out between 2010 and 2060), so the changes they need to do to be aligned with the mitigation strategy, are not as large as the changes in other regions in the medium term. Therefore, the co-benefits in these regions would be delayed. Second, when there is a limit on the availability of the CCS technologies, the regional allocation of the mitigation effort is modified. Therefore, some regions such as Japan and the Middle East have smaller CO_2 reductions assigned when there is a limit on CCS, reducing the mitigation cost. As CCS technologies are not as effective in reducing air pollutants, there is a reduction in policy costs in these regions with no significant consequences for health co-benefits.

Figure 5.16: Difference between the health co-benefit to mitigation cost ratio per region and scenario. Each scenario is compared against the "all available", represented by the dashed red line.



Sensitivity analysis: updated emission factors in China

Recent studies (Zheng et al., 2018) show that air pollutant emissions in China could be smaller than was initially expected due to the effective implementation of clean air policies in recent years. This would decrease pollutants in the baseline scenario and, therefore, the required effort to avoid pollutants in every policy scenario would also be reduced. Consequently, the calculated co-benefit for this region may be smaller than estimated here. While these newer emission factors were not included in the SSP assumptions used in this study, this subsection includes an additional calculation estimating results for China with these recent policies applied, which clearly underlines the importance of the taken assumptions. This comparison focuses on SO_2 because it varies the most when updating the EFs, and as it is the most influential specie for the formation of secondary $PM_{2.5}$.

Results in Zheng et al., 2018 imply that emission factors over this period would be lower, especially for SO_2, a major precursor for $PM_{2.5}$, than assumed in these GCAM scenarios. While, from 2010 to 2017, GCAM assumes that SO_2 would decrease around 16%, Zheng et al., 2018 estimates that this reduction was about 65%. For that reason, a sensitivity analysis has been performed by using updated EFs in GCAM in order to evaluate how these differences would affect to the calculated co-benefit in this region.

Air pollution standards outlined in Zheng et al 2018 have been fed into the model, to adjust NOx and SO_2 emissions factors for China from the electricity, cement, industrial combustion, and district heat sectors using GCAMv5.1.2, converting from mg/m^3 to Gg/PJ.[42] This comparison was performed with GCAMv5.1.2 since this version of the model has additional capabilities for setting air pollutant emission factor pathways that were not available in previous model versions. A linear reduction has been applied to emissions factors across time steps since GCAM runs in 5-year time slices to account for emission controls applied to existing industrial boilers and power plants. Air pollution standards have been incorporated as described in Zheng et al 2018 for China's NOx and SO_2 emissions from any new plants.

For coal fired power plants built in China in the 2010 and 2015 time periods in GCAM, hybrid emissions factors have been applied since 70% of existing plants met the ultra-low emissions standards in 2017 according to Zheng et al 2018. For plants built in 2010, half the plants are assumed to meet the existing unit standards (200 mg/m^3 for SO_2, 100 mg/m^3 for NOx), in effect from 2012-2015 (China's standard GB 13223-2011), and half the plants meet the ultra-low standards (35 mg/m^3 for SO_2 and 50 mg/m^3 NOx). For plants built in 2015, half of the plants are assumed to meet the new unit standards (100 mg/m^3 for SO_2 and NOx), in effect from 2012-2015 (China's standard GB 13223-2011), and half of the plants meet the ultra-low standards. For power plants built after 2015, all plants are assumed to meet the ultra-low standards. Finally, the fuel preference elasticity for coal use is adjusted in the residential sector to agree with 1990-2016 residential coal consumption trends from the China Statistical Yearbook 2017. The SO_2 emissions by sector of the applied and updated references and the ones reported in Zheng et al 2018 are summarized in Figure 5.17 .There is a reasonable agreement between the Zheng et al 2018 estimates of anthropogenic emissions from 2010 to 2017 and the 2015-2020 trend in China's SO_2 and NOx emissions from GCAM, given differences in base-year emission estimates.

This additional pollutant emission reduction in the baseline scenario (after updating EFs) will decrease reduction in pollutants in the climate policy scenarios, so the estimated health co-benefits would also be overestimated. Figure 5.18 shows the difference in SO_2 emissions for the policy scenarios of this study relative to the reference, compared to the difference in SO_2 relative to the reference with the updated EFs for China. For that, "2°C all available" scenario is replicated by running GCAMv5.1.2 with the updated EFs and relevant carbon prices from the GCAMv4.3 "All available" simulation. Then obtained SO_2 emissions are compared with the "reference with updated EFs" (run with GCAM 5.1.2). Therefore, it is possible compare reference and policy SO_2 emissions in a consistent way, although the GCAM versions used are not the same. The co-benefit in terms of reduced SO_2 emissions from the "all available" climate policy is 50-60% lower with updated emission factor pathways as compared to the SSP-based GCAM scenarios used in this chapter.

Finally, these divergences would consequently entail a different amount of premature deaths on this region. In order to capture the magnitude of the differences, Figure 5.19 compares the reference scenario used and the updated baseline scenario for China. It shows that the health co-benefits calculated in this study for this region may be overestimated in the short term (2020), with a difference of 181490 premature deaths (around 13%). However, the divergence would be reduced over the time horizon analyzed, becoming smaller than 54370 deaths (5%) in

[42]Data on coal properties from India was used for this conversion since this was readily available. Published sources differ substantial on coal properties in China. These assumptions do not significantly alter the conclusions since, in any case, current air pollution standards for the sectors above in China will result in much lower emissions regardless.

2050. Given the relatively large difference on SO_2 emission between the used and the updated reference scenarios, one might expect a larger difference in premature deaths. The reason why the difference is relatively small has to do with the $PM_{2.5}$ atmospheric composition. In the reference scenario used, in 2050, from the total atmospheric $PM_{2.5}$, around 63% are anthropogenic, from which 15% and 85% are primary and secondary particles, respectively. The secondary particles are composed of NO_3 (45%), NH_4 (28%) and SO_4 (27%), which is a 14% of the total atmospheric $PM_{2.5}$. Consequently, SO_2 variations, with other components unaltered, would have a significantly smaller impact on health.

Similarly, recent literature (Shi et al 2017) shows that GCAM estimations for SO_2 emissions in USA are overestimated compared to EPA projected inventories, mostly due to divergences in electric and transport (light duty vehicles) sectors. Concretely, total USA SO_2 emissions would differ from 22% to 60% relative to the reference scenario used from 2010 to 2025. Therefore, the potential SO_2 reduction and the associated health co-benefit would be overestimated. This confirms that assumptions for the baseline scenario are going to be important for determining the results. So, as said in Shi et al 2017, it is important to include national and subnational data into IAMs, which is planned to be explored in further research. If other air pollutant emissions are also overestimated in the version of GCAM used in this chapter, then this would likely further lower co-benefit estimates. Overall, this sensitivity exercise demonstrates that the assumed baseline air pollutant emission scenario will have an impact on the magnitude of co-benefit estimates.

Figure 5.17: SO_2 emissions per scenario for electricity (left) and industrial combustion (right) sectors (Tg)

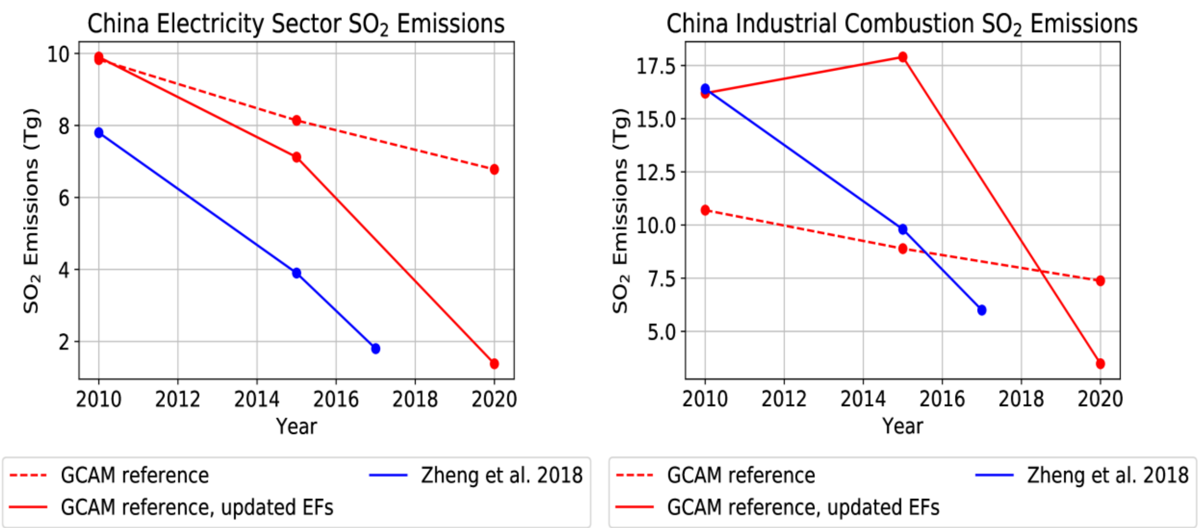


Figure 5.18: Avoided SO_2 (EM(ref)-Em(policy)) per period between policy and reference scenarios (Tg)

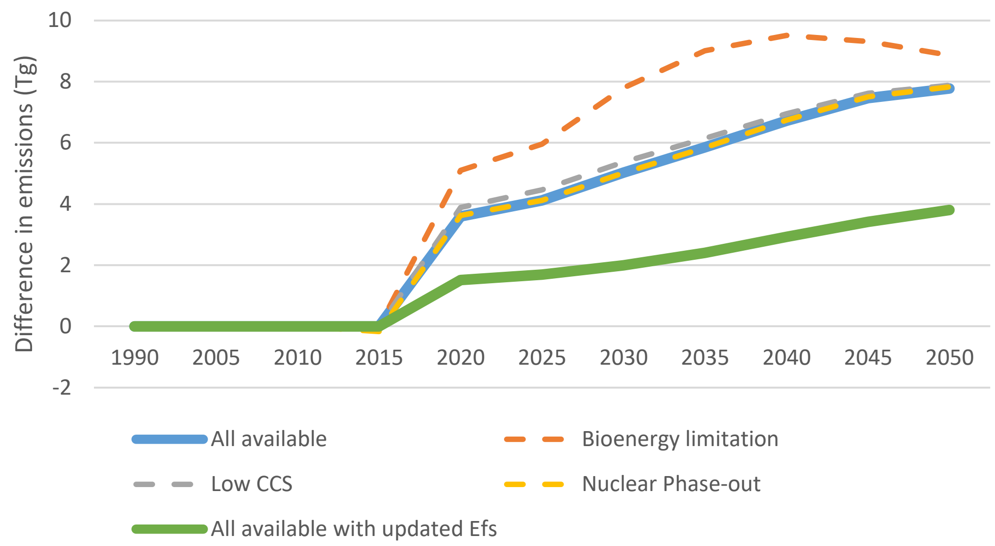
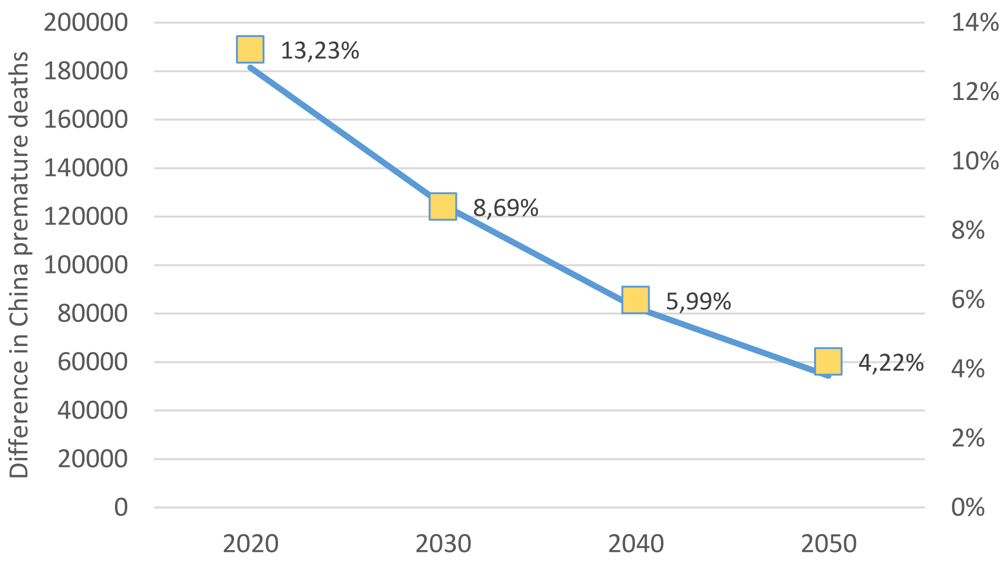


Figure 5.19: Difference in premature deaths in China between the current and the "updated EFs" reference scenarios by period. The results are shown in absolute (deaths) and relative (%) terms



Regional air Pollutant Reductions Relative to CO_2

With regard to the reductions of air pollutants, we highlight here the need for applying an integrated methodology since the emission reductions of each specie would have their own behavior over time, not necessarily following CO_2, as has been assumed in some previous work (Shindell et al., 2018). An assumption of proportional reductions among pollutants would not be accurate enough to capture these complex dynamics, as it is demonstrated in Figure 5.20.

Figure 5.20: Relative change in global air pollutants compared to CO_2, per scenario over the medium (2030) and long (2050) term.

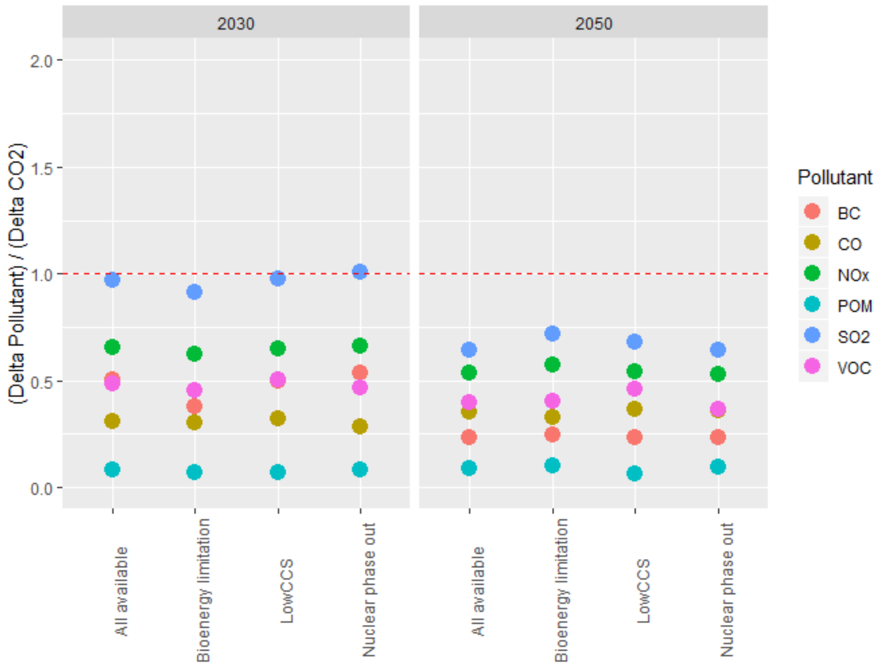
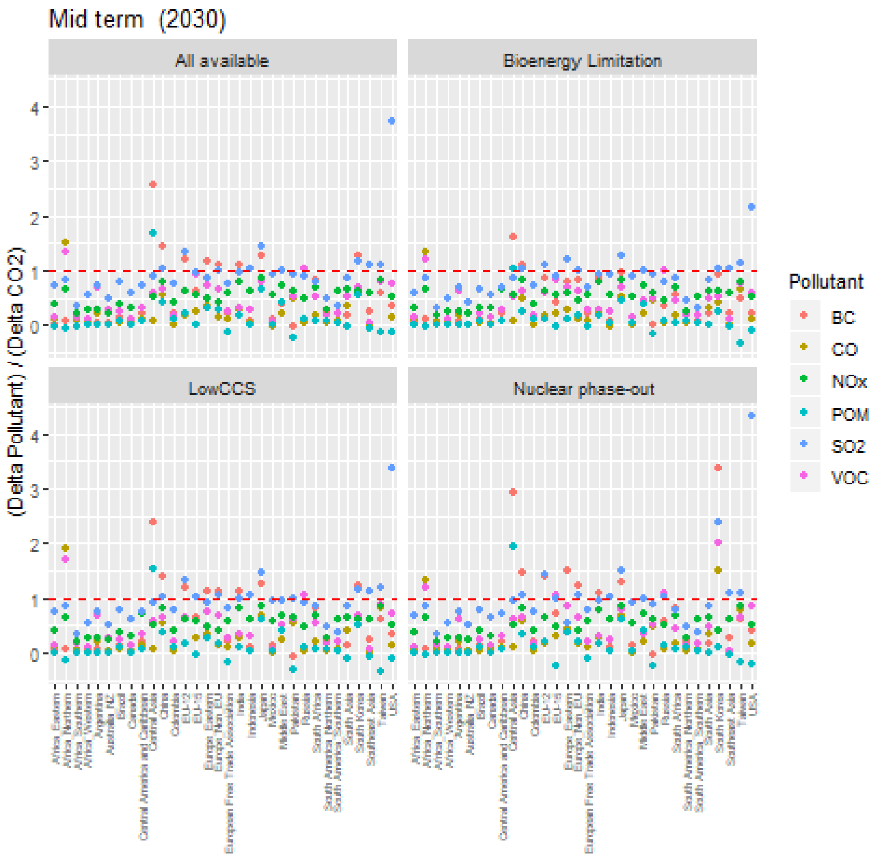
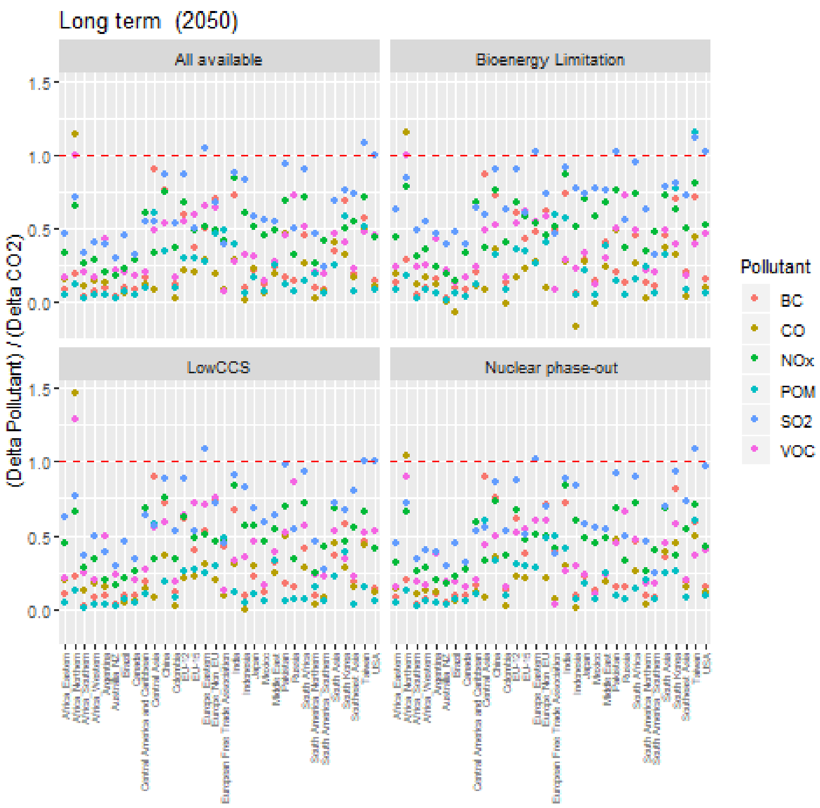


Figure 5.20 demonstrates that air pollutant reductions do not follow similar patterns and are not proportional to CO_2 reductions. Air pollutant reductions are generally smaller than CO_2 reductions, with large differences in the ratio per pollutant. NOx emissions decrease by 52-66% of the CO_2 reduction. This contrasts to POM emissions, which change relatively little (7-11% of CO_2). The ratio varies over time for SO_2 and BC, because as the century progresses with the deployment of emission controls reducing the remaining reduction potential. SO_2 reductions in the medium term (2030) are similar to those in CO_2 (92 – 102%), while in the longer term (2050) the change is smaller (64-71%). SO_2 reductions show the closest correspondence to CO_2 reductions, as has been noted previously (Van Vuuren et al 2008).

Similarly, Figure 5.21 disaggregates this information into the regional level. It shows that particulate organic matter (POM) and carbon monoxide (CO) have some negative values, what means that the emissions of these species would increase while CO_2 is decreasing. This effect, driven by the higher biomass use, demonstrates one of the possible externalities of the expansion of this technology. Second, Figure 5.20 indicates that the decrease in SO_2 emissions, in relative terms, would be similar to the CO_2 decrease in the medium term, while in the long term it would not. Figure 5.21 demonstrates that this effect is mainly driven by the USA, as the model assumes that this region would have a large potential to rapidly decrease SO_2 emissions, which may be overestimated as seen in previous subsection.

Figure 5.21: Regional relative changes in global air pollutants compared to CO_2, per scenario. The figures show the mid (2030) and long (2050) terms





Chapter 6

Conclusions and further research

Conclusions

The aim of this PhD Thesis is to evaluate air pollution driven health and agricultural impacts under different climate change scenarios. For that purpose, an innovative methodology has been developed that subsequently connects different models and tools in order to widen the perspective of climate policies. The application of this methodology to different climate scenarios have demonstrated the need of including these side effect into policy design based on the obtained outcomes, which may be of interest to a range of academics and stakeholders.

However, the use of models for prediction have some limitations, which have been shown during the PhD Thesis and reported in different studies (Pindyck, 2017). The large amount of assumptions that need to be taken in order to develop model-based climate policy analysis entails a certain degree of uncertainty in the results. As shown in Chapter 5, the assumptions of the baseline scenario and the definition of mitigation scenarios would directly affect to the final results. So, the framework and the taken assumptions should be carefully considered when analyzing the outcomes obtained from this kind of studies.

Nevertheless, integrated assessment models provide substantial insights to policy analysis, as they estimate future effects of different climate actions. The most influential institutions such as the Intergovernmental Panel on Climate Change (IPCC) or the International Energy Agency (IEA) include these modelling studies on their reports. Moreover, model-based research communities (such as IAM or "health co-benefit" communities) actively encourage to work on the refinement of the tools, in order to reduce the uncertainties. The accuracy of modeling results has become a key topic in recent years, with successful results as shown in different studies (e.g. Shi et al., 2017).

Taking this into consideration, some general conclusions can be drawn from this PhD thesis. First, Chapter 2 examines future O_3 impacts and the predicted effects on agricultural markets for a baseline scenario (no climate policy). Projected O_3 concentration levels would exceed the safe levels, so significant crop losses are expected in future periods, with the economic impacts that this would entail. This study draws two different conclusions: On the one hand, urgent action is needed to reduce emissions of O_3 precursors. The estimated losses will have severe effects on production levels and crop prices, which will directly affect land use changes and food security in developing countries. On the other hand, O_3 impacts should be factored into model simulation exercises, as the effects on agricultural markets can regionally modify resource allocation and crop production levels, which are significant aspects to be considered when estimating future results.

Moreover, inefficient policies such as fossil fuel subsidies (FFS) distort potential investments in clean energy sources, which are an essential element for reducing air pollution driven health impacts. The analysis in Chapter 3 shows that the phasing out and recycling of FFS into solar technologies would not suffice to meet climate targets, but it would contribute positively to efforts to meet certain targets such as CO_2 and air pollutant reduction, due to the increase of renewable energy in the electricity mix. Nevertheless, reductions in some pollutants (SO_2) would be offset by increases in others such as CO and OC, which are closely related to the expansion of bioenergy. Therefore, the impacts of air pollution driven side effects would not be significant and more stringent policies would be required in order to obtain significant health or agricultural co-benefits.

In that framework, the subsequent chapters analyze the health co-benefits associated with different transition pathways. Chapter 4 focuses on two different long-term temperature targets

(1.5°C and 2°C) where mitigation efforts are shared between countries following three established equity criteria. Chapter 5 analyzes the potential co-benefits of meeting the 2°C target under different technological scenarios. These chapters conclude that for most scenarios health co-benefits would outweigh the mitigation costs of each strategy at global level. In some countries, such as India or China, health co-benefits would significantly outweigh costs, while in others they would cover a substantial part of the associated cost. Moreover, to address the uncertainty of the assumptions (e.g. emission coefficients or VSL), various sensitivity analyses are performed which demonstrate the robustness of the results obtained. Consequently, the health co-benefits analysis developed in this thesis might encourage policy makers to consider these side effects in policy design, given that they might increase the cost-effectiveness of different climate strategies.

Further Research

The integrated modeling framework developed and the studies carried out in the course of this thesis have opened up a wide range of new research questions. First, there are more and more studies which analyze health co-benefits at a global level, but with limited information on national and regional scales. As many countries are now defining their national climate strategies, the addition of potential side-effects can provide valuable insights for policy makers. Consequently, there is an emerging need to downscale health co-benefit analysis in order to conduct national or regional studies which can encourage stakeholders to consider these effects in the design of climate strategies. As an example, the Spanish government has recently incorporated the methodology developed here in its *Plan Nacional Integrado de Energía y Clima* (PNIEC) 2021-2030[43]", on which I had occasion to work. This is the first step towards applying this work to national/regional strategies, increasing the possibilities of extending the methodology to further specific mitigation plans.

Another ongoing study in this line arising from this PhD thesis is the estimation of health co-benefits from air pollutant reduction due to the shutting down of coal-fired power plants, which is a key topic in current climate debate. That study compares the co-benefits of phasing out coal with those of applying NDCs globally. Preliminary results show that in the medium term some regions can obtain greater co-benefits by shutting down coal-fired power plants. I am also collaborating with the World Health Organization on a project to analyze the uncertainty in the results (from Chapters 4 and 5). Under the project name "A sensitivity analysis of modelling health co-benefits of global climate mitigation commitments", various researchers are expected to apply their modelling methods to compare the health outcomes of a single mitigation scenario (2°C, "least cost" approach). This study not only reveals the extent to which the results of different modelling groups are similar, but also serves to analyze the isolated effect of different inputs in order to identify which assumptions/parameters are more (and less) uncertain.

Finally, the study of O_3 implications is another contribution to the field, but some limitations need to be analyzed. Further research should consider various aspects, such as the fact that the isolated analysis of O_3 is failing to capture the interaction of this pollutant with other harmful effects. A follow-up study will analyze the combined effects of O_3, the carbon fertilization effect (CFE), and climate variables, measured as changes in temperature and precipitation. Yet another

[43] https://www.miteco.gob.es/es/cambio-climatico/participacion-publica/documentoparticipacionpublicaborradordelplannacionalintegradodeenergiayclima2021-2030_tcm30-487344.pdf"

research line open is the analysis of the marginal effects of different O_3 precursors on crop yields. Identifying the most harmful pollutants in each region would enable national policy makers to determine the most effective policy for reducing potential O_3 effects. Finally, another interesting line of research would be to explore how O_3 effects on agricultural productivity can affect food security in different climate scenarios, including those of the Paris Agreement.

ANNEX I: GCAM and TM5-FASST regions

COUNTRY	ISO 3	GCAM REGION	TM5-FASST REGION
BURUNDI	BDI	Africa_Eastern	EAF
COMOROS	COM	Africa_Eastern	EAF
DJIBOUTI	DJI	Africa_Eastern	EAF
ERITREA	ERI	Africa_Eastern	EAF
ETHIOPIA	ETH	Africa_Eastern	EAF
KENYA	KEN	Africa_Eastern	EAF
MADAGASCAR	MDG	Africa_Eastern	EAF
MAURITIUS	MUS	Africa_Eastern	EAF
REUNION	REU	Africa_Eastern	EAF
RWANDA	RWA	Africa_Eastern	EAF
SUDAN	SDN	Africa_Eastern	EAF
SOMALIA	SOM	Africa_Eastern	EAF
UGANDA	UGA	Africa_Eastern	EAF
EGYPT	EGY	Africa_Northern	EGY
ALGERIA	DZA	Africa_Northern	NOA
WESTERN SAHARA	ESH	Africa_Northern	NOA
LIBYAN ARAB JAMAHIRIYA	LBY	Africa_Northern	NOA
MOROCCO	MAR	Africa_Northern	NOA
TUNISIA	TUN	Africa_Northern	NOA
TANZANIA, UNITED REPUBLIC OF	TZA	Africa_Southern	EAF
LESOTHO	LSO	Africa_Southern	RSA
SWAZILAND	SWZ	Africa_Southern	RSA
ANGOLA	AGO	Africa_Southern	SAF
BOTSWANA	BWA	Africa_Southern	SAF
MOZAMBIQUE	MOZ	Africa_Southern	SAF
MALAWI	MWI	Africa_Southern	SAF
NAMIBIA	NAM	Africa_Southern	SAF
ZAMBIA	ZMB	Africa_Southern	SAF
ZIMBABWE	ZWE	Africa_Southern	SAF
CENTRAL AFRICAN REPUBLIC	CAF	Africa_Western	EAF
CONGO, Democratic Republic of (was Zaire)	COD	Africa_Western	EAF
CHAD	TCD	Africa_Western	EAF
BENIN	BEN	Africa_Western	WAF
BURKINA FASO	BFA	Africa_Western	WAF
COTE D'IVOIRE	CIV	Africa_Western	WAF
CAMEROON	CMR	Africa_Western	WAF
CONGO, Republic of	COG	Africa_Western	WAF
CAPE VERDE	CPV	Africa_Western	WAF
GABON	GAB	Africa_Western	WAF
GHANA	GHA	Africa_Western	WAF
GUINEA	GIN	Africa_Western	WAF
GAMBIA	GMB	Africa_Western	WAF

GUINEA-BISSAU	GNB	Africa_Western	WAF
EQUATORIAL GUINEA	GNQ	Africa_Western	WAF
LIBERIA	LBR	Africa_Western	WAF
MALI	MLI	Africa_Western	WAF
MAURITANIA	MRT	Africa_Western	WAF
NIGER	NER	Africa_Western	WAF
NIGERIA	NGA	Africa_Western	WAF
SENEGAL	SEN	Africa_Western	WAF
SIERRA LEONE	SLE	Africa_Western	WAF
SAO TOME AND PRINCIPE	STP	Africa_Western	WAF
TOGO	TGO	Africa_Western	WAF
ARGENTINA	ARG	Argentina	ARG
AUSTRALIA	AUS	Australia_NZ	AUS
NEW ZEALAND	NZL	Australia_NZ	NZL
BRAZIL	BRA	Brazil	BRA
ARUBA	ABW	CAC	RCAM
ANGUILLA	AIA	CAC	RCAM
NETHERLANDS ANTILLES	ANT	CAC	RCAM
ANTIGUA AND BARBUDA	ATG	CAC	RCAM
BAHAMAS	BHS	CAC	RCAM
BELIZE	BLZ	CAC	RCAM
BARBADOS	BRB	CAC	RCAM
COSTA RICA	CRI	CAC	RCAM
CUBA	CUB	CAC	RCAM
CAYMAN ISLANDS	CYM	CAC	RCAM
DOMINICA	DMA	CAC	RCAM
DOMINICAN REPUBLIC	DOM	CAC	RCAM
GUADELOUPE	GLP	CAC	RCAM
GRENADA	GRD	CAC	RCAM
GUATEMALA	GTM	CAC	RCAM
HONDURAS	HND	CAC	RCAM
HAITI	HTI	CAC	RCAM
JAMAICA	JAM	CAC	RCAM
SAINT KITTS AND NEVIS	KNA	CAC	RCAM
SAINT LUCIA	LCA	CAC	RCAM
MONTSERRAT	MSR	CAC	RCAM
MARTINIQUE	MTQ	CAC	RCAM
NICARAGUA	NIC	CAC	RCAM
PANAMA	PAN	CAC	RCAM
EL SALVADOR	SLV	CAC	RCAM
TRINIDAD AND TOBAGO	TTO	CAC	RCAM
SAINT VINCENT AND THE GRENADINES	VCT	CAC	RCAM
BERMUDA	BMU	CAC	USA
CANADA	CAN	Canada	CAN

KAZAKHSTAN	KAZ	Central Asia	KAZ
MONGOLIA	MNG	Central Asia	MON
KYRGYZSTAN	KGZ	Central Asia	RIS
TAJIKISTAN	TJK	Central Asia	RIS
TURKMENISTAN	TKM	Central Asia	RIS
UZBEKISTAN	UZB	Central Asia	RIS
ARMENIA	ARM	Central Asia	RUS
AZERBAIJAN	AZE	Central Asia	RUS
GEORGIA	GEO	Central Asia	RUS
CHINA	CHN	China	CHN
HONG KONG	HKG	China	CHN
MACAU	MAC	China	CHN
COLOMBIA	COL	Colombia	RSAM
SLOVENIA	SVN	EU-12	AUT
BULGARIA	BGR	EU-12	BGR
CYPRUS	CYP	EU-12	GRC
HUNGARY	HUN	EU-12	HUN
MALTA	MLT	EU-12	ITA
ESTONIA	EST	EU-12	POL
LITHUANIA	LTU	EU-12	POL
LATVIA	LVA	EU-12	POL
POLAND	POL	EU-12	POL
CZECH REPUBLIC	CZE	EU-12	RCZ
SLOVAKIA	SVK	EU-12	RCZ
ROMANIA	ROU	EU-12	ROM
FALKLAND ISLANDS (MALVINAS)	FLK	EU-15	ARG
AUSTRIA	AUT	EU-15	AUT
BELGIUM	BEL	EU-15	BLX
LUXEMBOURG	LUX	EU-15	BLX
NETHERLANDS	NLD	EU-15	BLX
GREENLAND	GRL	EU-15	CAN
SPAIN	ESP	EU-15	ESP
GIBRALTAR	GIB	EU-15	ESP
PORTUGAL	PRT	EU-15	ESP
FINLAND	FIN	EU-15	FIN
ANDORRA	AND	EU-15	FRA
FRANCE	FRA	EU-15	FRA
UNITED KINGDOM	GBR	EU-15	GBR
IRELAND	IRL	EU-15	GBR
GREECE	GRC	EU-15	GRC
ITALY	ITA	EU-15	ITA
MONACO	MCO	EU-15	ITA
SAN MARINO	SMR	EU-15	ITA
VATICAN CITY STATE (HOLY SEE)	VAT	EU-15	ITA

WALLIS AND FUTUNA ISLANDS	WLF	EU-15	PAC
TURKS AND CAICOS ISLANDS	TCA	EU-15	RCAM
VIRGIN ISLANDS (BRITISH)	VGB	EU-15	RCAM
GERMANY	DEU	EU-15	RFA
DENMARK	DNK	EU-15	SWE
FAROE ISLANDS	FRO	EU-15	SWE
SWEDEN	SWE	EU-15	SWE
SAINT PIERRE AND MIQUELON	SPM	EU-15	USA
SAINT HELENA	SHN	EU-15	WAF
LIECHTENSTEIN	LIE	Europe FTA	AUT
SWITZERLAND	CHE	Europe FTA	CHE
ICELAND	ISL	Europe FTA	NOR
NORWAY	NOR	Europe FTA	NOR
SVALBARD AND JAN MAYEN ISLANDS	SJM	Europe FTA	NOR
BELARUS	BLR	Europe_Eastern	UKR
MOLDOVA, REPUBLIC OF	MDA	Europe_Eastern	UKR
UKRAINE	UKR	Europe_Eastern	UKR
ALBANIA	ALB	Europe_Non_EU	RCEU
BOSNIA AND HERZEGOWINA	BIH	Europe_Non_EU	RCEU
CROATIA (local name: Hrvatska)	HRV	Europe_Non_EU	RCEU
MACEDONIA, THE FORMER YUGOSLAV REPUBLIC OF	MKD	Europe_Non_EU	RCEU
SERBIA AND MONTENEGRO	SCG	Europe_Non_EU	RCEU
TURKEY	TUR	Europe_Non_EU	TUR
INDIA	IND	India	NDE
INDONESIA	IDN	Indonesia	IDN
JAPAN	JPN	Japan	JPN
MEXICO	MEX	Mexico	MEX
UNITED ARAB EMIRATES	ARE	Middle East	GOLF
BAHRAIN	BHR	Middle East	GOLF
IRAN (ISLAMIC REPUBLIC OF)	IRN	Middle East	GOLF
IRAQ	IRQ	Middle East	GOLF
KUWAIT	KWT	Middle East	GOLF
OMAN	OMN	Middle East	GOLF
QATAR	QAT	Middle East	GOLF
SAUDI ARABIA	SAU	Middle East	GOLF
YEMEN	YEM	Middle East	GOLF
ISRAEL	ISR	Middle East	MEME
JORDAN	JOR	Middle East	MEME
LEBANON	LBN	Middle East	MEME
PALESTINIAN TERRITORY, Occupied	PSE	Middle East	MEME
SYRIAN ARAB REPUBLIC	SYR	Middle East	MEME
PAKISTAN	PAK	Pakistan	RSAS
RUSSIAN FEDERATION	RUS	Russia	RUS
SOUTH AFRICA	ZAF	South Africa	RSA

FRENCH GUIANA	GUF	South America_Northern	RSAM
GUYANA	GUY	South America_Northern	RSAM
SURINAME	SUR	South America_Northern	RSAM
VENEZUELA	VEN	South America_Northern	RSAM
URUGUAY	URY	South America_Southern	ARG
CHILE	CHL	South America_Southern	CHL
BOLIVIA	BOL	South America_Southern	RSAM
ECUADOR	ECU	South America_Southern	RSAM
PERU	PER	South America_Southern	RSAM
PARAGUAY	PRY	South America_Southern	RSAM
SRI LANKA	LKA	South Asia	NDE
MALDIVES	MDV	South Asia	NDE
AFGHANISTAN	AFG	South Asia	RSAS
BANGLADESH	BGD	South Asia	RSAS
BHUTAN	BTN	South Asia	RSAS
NEPAL	NPL	South Asia	RSAS
KOREA, REPUBLIC OF	KOR	South Korea	COR
SEYCHELLES	SYC	Southeast Asia	EAF
TIMOR-LESTE	TLS	Southeast Asia	IDN
KOREA, DEMOCRATIC PEOPLE'S REPUBLIC OF	PRK	Southeast Asia	MON
BRUNEI DARUSSALAM	BRN	Southeast Asia	MYS
MALAYSIA	MYS	Southeast Asia	MYS
SINGAPORE	SGP	Southeast Asia	MYS
AMERICAN SAMOA	ASM	Southeast Asia	PAC
COOK ISLANDS	COK	Southeast Asia	PAC
FIJI	FJI	Southeast Asia	PAC
MICRONESIA, FEDERATED STATES OF	FSM	Southeast Asia	PAC
GUAM	GUM	Southeast Asia	PAC
KIRIBATI	KIR	Southeast Asia	PAC
MARSHALL ISLANDS	MHL	Southeast Asia	PAC
NORTHERN MARIANA ISLANDS	MNP	Southeast Asia	PAC
NEW CALEDONIA	NCL	Southeast Asia	PAC
NORFOLK ISLAND	NFK	Southeast Asia	PAC
NIUE	NIU	Southeast Asia	PAC
NAURU	NRU	Southeast Asia	PAC
PITCAIRN	PCN	Southeast Asia	PAC
PALAU	PLW	Southeast Asia	PAC
PAPUA NEW GUINEA	PNG	Southeast Asia	PAC
FRENCH POLYNESIA	PYF	Southeast Asia	PAC
SOLOMON ISLANDS	SLB	Southeast Asia	PAC
TOKELAU	TKL	Southeast Asia	PAC
TONGA	TON	Southeast Asia	PAC
TUVALU	TUV	Southeast Asia	PAC
VANUATU	VUT	Southeast Asia	PAC

SAMOA	WSM	Southeast Asia	PAC
PHILIPPINES	PHL	Southeast Asia	PHL
CAMBODIA	KHM	Southeast Asia	RSEA
LAO PEOPLE'S DEMOCRATIC REPUBLIC	LAO	Southeast Asia	RSEA
MYANMAR	MMR	Southeast Asia	RSEA
MAYOTTE	MYT	Southeast Asia	SAF
THAILAND	THA	Southeast Asia	THA
VIET NAM	VNM	Southeast Asia	VNM
TAIWAN	TWN	Taiwan	TWN
PUERTO RICO	PRI	USA	RCAM
VIRGIN ISLANDS (U.S.)	VIR	USA	RCAM
UNITED STATES	USA	USA	USA

ANNEX II: Crop commodities in GCAM

Item	GCAM commodity	GCAM Crop category
Maize	Corn	Staple crop
Maize, green	Corn	Staple crop
Popcorn	Corn	Staple crop
Agave Fibres Nes	FiberCrop	Non-staple crop
Coir	FiberCrop	Non-staple crop
Fibre Crops Nes	FiberCrop	Non-staple crop
Flax fibre and tow	FiberCrop	Non-staple crop
Hemp Tow Waste	FiberCrop	Non-staple crop
Jute	FiberCrop	Non-staple crop
Manila Fibre (Abaca)	FiberCrop	Non-staple crop
Other Bastfibres	FiberCrop	Non-staple crop
Ramie	FiberCrop	Non-staple crop
Seed cotton	FiberCrop	Non-staple crop
Sisal	FiberCrop	Non-staple crop
forage Products	FodderGrass	Feed crop
Rye grass for forage & silage	FodderGrass	Feed crop
Alfalfa for forage and silage	FodderHerb	Feed crop
Beets for Fodder	FodderHerb	Feed crop
Cabbage for Fodder	FodderHerb	Feed crop
Carrots for Fodder	FodderHerb	Feed crop
Clover for forage and silage	FodderHerb	Feed crop
Green Oilseeds for Silage	FodderHerb	Feed crop
Leguminous for Silage	FodderHerb	Feed crop
Maize for forage and silage	FodderHerb	Feed crop
Sorghum for forage and silage	FodderHerb	Feed crop
Swedes for Fodder	FodderHerb	Feed crop
Turnips for Fodder	FodderHerb	Feed crop
Vegetables Roots Fodder	FodderHerb	Feed crop
Vetches	FodderHerb	Feed crop
Almonds, with shell	MiscCrop	Non-staple crop
Anise, badian, fennel, corian.	MiscCrop	Non-staple crop
Apples	MiscCrop	Non-staple crop
Apricots	MiscCrop	Non-staple crop
Arecanuts	MiscCrop	Non-staple crop
Artichokes	MiscCrop	Non-staple crop
Asparagus	MiscCrop	Non-staple crop
Avocados	MiscCrop	Non-staple crop
Bambara beans	MiscCrop	Non-staple crop
Bananas	MiscCrop	Non-staple crop
Beans, dry	MiscCrop	Non-staple crop
Beans, green	MiscCrop	Non-staple crop
Berries Nes	MiscCrop	Non-staple crop

Blueberries	MiscCrop	Non-staple crop
Brazil nuts, with shell	MiscCrop	Non-staple crop
Broad beans, horse beans, dry	MiscCrop	Non-staple crop
Cabbages and other brassicas	MiscCrop	Non-staple crop
Carobs	MiscCrop	Non-staple crop
Carrots and turnips	MiscCrop	Non-staple crop
Cashew nuts, with shell	MiscCrop	Non-staple crop
Cashewapple	MiscCrop	Non-staple crop
Cauliflowers and broccoli	MiscCrop	Non-staple crop
Cherries	MiscCrop	Non-staple crop
Chestnuts	MiscCrop	Non-staple crop
Chick peas	MiscCrop	Non-staple crop
Chicory roots	MiscCrop	Non-staple crop
Chillies and peppers, dry	MiscCrop	Non-staple crop
Chillies and peppers, green	MiscCrop	Non-staple crop
Cinnamon (canella)	MiscCrop	Non-staple crop
Citrus fruit, nes	MiscCrop	Non-staple crop
Cloves	MiscCrop	Non-staple crop
Cocoa beans	MiscCrop	Non-staple crop
Coffee, green	MiscCrop	Non-staple crop
Cow peas, dry	MiscCrop	Non-staple crop
Cranberries	MiscCrop	Non-staple crop
Cucumbers and gherkins	MiscCrop	Non-staple crop
Currants	MiscCrop	Non-staple crop
Dates	MiscCrop	Non-staple crop
Eggplants (aubergines)	MiscCrop	Non-staple crop
Figs	MiscCrop	Non-staple crop
Fruit Fresh Nes	MiscCrop	Non-staple crop
Fruit, tropical fresh nes	MiscCrop	Non-staple crop
Garlic	MiscCrop	Non-staple crop
Ginger	MiscCrop	Non-staple crop
Gooseberries	MiscCrop	Non-staple crop
Grapefruit (inc. pomelos)	MiscCrop	Non-staple crop
Grapes	MiscCrop	Non-staple crop
Hazelnuts, with shell	MiscCrop	Non-staple crop
Hops	MiscCrop	Non-staple crop
Kiwi fruit	MiscCrop	Non-staple crop
Kolanuts	MiscCrop	Non-staple crop
Leeks, other alliaceous veg	MiscCrop	Non-staple crop
Leguminous vegetables, nes	MiscCrop	Non-staple crop
Lemons and limes	MiscCrop	Non-staple crop
Lentils	MiscCrop	Non-staple crop
Lettuce and chicory	MiscCrop	Non-staple crop
Lupins	MiscCrop	Non-staple crop

Mangoes, mangosteens, guavas	MiscCrop	Non-staple crop
Mate	MiscCrop	Non-staple crop
Mushrooms and truffles	MiscCrop	Non-staple crop
Nutmeg, mace and cardamoms	MiscCrop	Non-staple crop
Nuts, nes	MiscCrop	Non-staple crop
Okra	MiscCrop	Non-staple crop
Onions (inc. shallots), green	MiscCrop	Non-staple crop
Onions, dry	MiscCrop	Non-staple crop
Oranges	MiscCrop	Non-staple crop
Other melons (inc.cantaloupes)	MiscCrop	Non-staple crop
Papayas	MiscCrop	Non-staple crop
Peaches and nectarines	MiscCrop	Non-staple crop
Pears	MiscCrop	Non-staple crop
Peas, dry	MiscCrop	Non-staple crop
Peas, green	MiscCrop	Non-staple crop
Pepper (Piper spp.)	MiscCrop	Non-staple crop
Peppermint	MiscCrop	Non-staple crop
Persimmons	MiscCrop	Non-staple crop
Pigeon peas	MiscCrop	Non-staple crop
Pineapples	MiscCrop	Non-staple crop
Pistachios	MiscCrop	Non-staple crop
Plantains	MiscCrop	Non-staple crop
Plums and sloes	MiscCrop	Non-staple crop
Pome fruit, nes	MiscCrop	Non-staple crop
Pulses, nes	MiscCrop	Non-staple crop
Pumpkins, squash and gourds	MiscCrop	Non-staple crop
Pyrethrum,Dried	MiscCrop	Non-staple crop
Quinces	MiscCrop	Non-staple crop
Raspberries	MiscCrop	Non-staple crop
Sour cherries	MiscCrop	Non-staple crop
Spices, nes	MiscCrop	Non-staple crop
Spinach	MiscCrop	Non-staple crop
Stone fruit, nes	MiscCrop	Non-staple crop
Strawberries	MiscCrop	Non-staple crop
String beans	MiscCrop	Non-staple crop
Tallowtree Seeds	MiscCrop	Non-staple crop
Tangerines, mandarins, clem.	MiscCrop	Non-staple crop
Tea	MiscCrop	Non-staple crop
Tea Nes	MiscCrop	Non-staple crop
Tobacco, unmanufactured	MiscCrop	Non-staple crop
Tomatoes	MiscCrop	Non-staple crop
Vanilla	MiscCrop	Non-staple crop
Vegetables fresh nes	MiscCrop	Non-staple crop
Walnuts, with shell	MiscCrop	Non-staple crop

Watermelons	MiscCrop	Non-staple crop
Castor oil seed	OilCrop	Non-staple crop
Groundnuts, with shell	OilCrop	Non-staple crop
Hempseed	OilCrop	Non-staple crop
Jojoba Seeds	OilCrop	Non-staple crop
Kapok Fruit	OilCrop	Non-staple crop
Karite Nuts (Sheanuts)	OilCrop	Non-staple crop
Linseed	OilCrop	Non-staple crop
Melonseed	OilCrop	Non-staple crop
Mustard seed	OilCrop	Non-staple crop
Oilseeds, Nes	OilCrop	Non-staple crop
Olives	OilCrop	Non-staple crop
Poppy seed	OilCrop	Non-staple crop
Rapeseed	OilCrop	Non-staple crop
Safflower seed	OilCrop	Non-staple crop
Sesame seed	OilCrop	Non-staple crop
Soybeans	OilCrop	Non-staple crop
Sunflower seed	OilCrop	Non-staple crop
Tung Nuts	OilCrop	Non-staple crop
Barley	OtherGrain	Staple crop
Buckwheat	OtherGrain	Staple crop
Canary seed	OtherGrain	Staple crop
Cereals, nes	OtherGrain	Staple crop
Fonio	OtherGrain	Staple crop
Millet	OtherGrain	Staple crop
Mixed grain	OtherGrain	Staple crop
Oats	OtherGrain	Staple crop
Quinoa	OtherGrain	Staple crop
Rye	OtherGrain	Staple crop
Sorghum	OtherGrain	Staple crop
Triticale	OtherGrain	Staple crop
Coconuts	PalmFruit	Non-staple crop
Oil palm fruit	PalmFruit	Non-staple crop
Rice, paddy	Rice	Staple crop
Cassava	Root_Tuber	Staple crop
Potatoes	Root_Tuber	Staple crop
Roots and Tubers, nes	Root_Tuber	Staple crop
Sweet potatoes	Root_Tuber	Staple crop
Taro (cocoyam)	Root_Tuber	Staple crop
Yams	Root_Tuber	Staple crop
Yautia (cocoyam)	Root_Tuber	Staple crop
Sugar beet	SugarCrop	Non-staple crop
Sugar cane	SugarCrop	Non-staple crop
Sugar crops, nes	SugarCrop	Non-staple crop

Wheat	Wheat	Staple crop

ANNEX III: VSL per region and period

The following table shows which are the values for the TM5-FASST 56 regions, calculated as explained in the *methodology* subsection. The numbers include the adjusted VSL and the 10% increase of the morbidity costs. The values in brackets show the lower and upper bounds.

	2020	*2030*	*2040*	*2050*
	MedValue	**MedValue**	**MedValue**	**MedValue**
ARG	3·04 (1·52;4·57)	3·64 (1·82;5·45)	4·16 (2·08;6·25)	4·79 (2·40;7·19)
AUS	7.59 (3.79;11.38)	9.02 (4.51;13.52)	10.12 (5.06;15.19)	10.96 (5.48;16.45)
AUT	5.68 (2.84;8.53)	5.90 (2.95;8.85)	6.34 (3.17;9.51)	6.89 (3.45;10.34)
BGR	2.98 (1.49;4.47)	3.53 (1.76;5.29)	3.90 (1.95;5.86)	4.26 (2.13;6.39)
BLX	7.15 (3.58;10.73)	8.66 (4.33;13.00)	9.99 (4.99;14.98)	11.14 (5.57;16.71)
BRA	2.36 (1.18;3.54)	2.77 (1.38;4.15)	3.19 (1.60;4.79)	3.86 (1.93;5.79)
CAN	6.26 (3.13;9.38)	7.24 (3.62;10.85)	8.10 (4.05;12.15)	8.79 (4.40;13.19)
CHE	6.47 (3.23;9.70)	6.94 (3.47;10.41)	7.57 (3.78;11.35)	8.29 (4.15;12.44)
CHL	2.72 (1.36;4.09)	3.20 (1.60;4.80)	3.77 (1.88;5.65)	4.32 (2.16;6.48)
CHN	3.13 (1.56;4.69)	4.47 (2.23;6.70)	5.36 (2.68;8.04)	6.04 (3.02;9.06)
COR	4.48 (2.24;6.72)	4.56 (2.28;6.84)	4.88 (2.44;7.31)	5.24 (2.62;7.87)
EAF	0.43 (0.21;0.64)	0.58 (0.29;0.86)	0.76 (0.38;1.13)	0.95 (0.47;1.42)
EGY	1.45 (0.72;2.17)	1.76 (0.88;2.64)	2.17 (1.09;3.26)	2.67 (1.33;4.00)
ESP	5.22 (2.61;7.83)	6.55 (3.28;9.83)	7.84 (3.92;11.76)	8.94 (4.47;13.41)
FIN	5.74 (2.87;8.62)	6.61 (3.30;9.91)	7.40 (3.70;11.10)	8.11 (4.05;12.16)
FRA	5.86 (2.93;8.79)	7.40 (3.70;11.10)	8.82 (4.41;13.22)	10.00 (5.00;15.00)
GBR	6.26 (3.13;9.40)	7.95 (3.98;11.93)	9.49 (4.75;14.24)	10.75 (5.37;16.12)
GOLF	3.00 (1.50;4.50)	3.61 (1.80;5.41)	4.20 (2.10;6.30)	4.71 (2.36;7.07)
GRC	5.31 (2.65;7.96)	6.68 (3.34;10.02)	8.07 (4.04;12.11)	9.29 (4.65;13.94)
HUN	3.64 (1.82;5.47)	4.41 (2.20;6.61)	5.02 (2.51;7.53)	5.56 (2.78;8.34)
IDN	1.66 (0.83;2.49)	2.54 (1.27;3.80)	3.24 (1.62;4.85)	3.90 (1.95;5.85)
ITA	5.52 (2.76;8.29)	7.40 (3.70;11.10)	9.02 (4.51;13.53)	10.28 (5.14;15.41)
JPN	5.21 (2.61;7.82)	5.63 (2.82;8.45)	6.18 (3.09;9.26)	6.75 (3.38;10.13)
KAZ	3.69 (1.85;5.54)	4.38 (2.19;6.58)	4.67 (2.33;7.00)	4.96 (2.48;7.44)
MEME	2.03 (1.01;3.04)	2.29 (1.14;3.43)	2.65 (1.33;3.98)	3.07 (1.53;4.60)
MEX	2.66 (1.33;4.00)	3.27 (1.64;4.91)	3.91 (1.95;5.86)	4.63 (2.31;6.94)
MON	0.30 (0.15;0.45)	0.35 (0.18;0.53)	0.41 (0.20;0.61)	0.48 (0.24;0.71)
MYS	3.50 (1.75;5.25)	3.88 (1.94;5.82)	4.42 (2.21;6.62)	4.97 (2.48;7.45)
NDE	1.55 (0.78;2.33)	2.44 (1.22;3.66)	3.10 (1.55;4.65)	3.58 (1.79;5.37)
NOA	1.47 (0.74;2.21)	1.66 (0.83;2.49)	2.05 (1.02;3.07)	2.55 (1.27;3.82)
NOR	8.15 (4.07;12.22)	9.51 (4.75;14.26)	10.62 (5.31;15.93)	11.54 (5.77;17.31)
NZL	5.17 (2.59;7.76)	5.91 (2.95;8.86)	6.60 (3.30;9.89)	7.25 (3.62;10.87)
PAC	1.07 (0.53;1.60)	1.36 (0.68;2.04)	1.77 (0.89;2.66)	2.36 (1.18;3.53)
PHL	0.93 (0.47;1.40)	1.17 (0.59;1.76)	1.49 (0.75;2.24)	1.87 (0.93;2.80)
POL	4.09 (2.05;6.14)	4.92 (2.46;7.38)	5.39 (2.70;8.09)	5.82 (2.91;8.73)
RCAM	2.01 (1.01;3.02)	2.27 (1.14;3.41)	2.60 (1.30;3.89)	2.99 (1.49;4.48)
RCEU	2.71 (1.36;4.07)	3.57 (1.79;5.36)	4.22 (2.11;6.33)	4.75 (2.38;7.13)

RCZ	4.17 (2.09;6.26)	4.28 (2.14;6.42)	4.61 (2.31;6.92)	5.06 (2.53;7.59)
RFA	5.20 (2.60;7.80)	5.37 (2.69;8.06)	5.81 (2.91;8.72)	6.41 (3.21;9.62)
RIS	1.80 (0.90;2.70)	3.60 (1.80;5.41)	4.67 (2.34;7.01)	5.14 (2.57;7.71)
ROM	2.94 (1.47;4.41)	3.84 (1.92;5.76)	4.47 (2.23;6.70)	4.98 (2.49;7.47)
RSA	1.92 (0.96;2.87)	2.39 (1.19;3.58)	3.03 (1.51;4.54)	3.69 (1.84;5.53)
RSAM	2.01 (1.00;3.01)	2.48 (1.24;3.72)	2.91 (1.45;4.36)	3.39 (1.69;5.08)
RSAS	0.61 (0.30;0.91)	0.72 (0.36;1.07)	0.89 (0.45;1.34)	1.15 (0.58;1.73)
RSEA	0.74 (0.37;1.11)	1.05 (0.52;1.57)	1.34 (0.67;2.01)	1.64 (0.82;2.46)
RUE	1.17 (0.59;1.76)	1.35 (0.68;2.03)	1.48 (0.74;2.22)	1.61 (0.81;2.42)
RUS	4.24 (2.12;6.35)	4.94 (2.47;7.41)	5.39 (2.69;8.08)	5.86 (2.93;8.79)
SAF	0.75 (0.38;1.13)	0.85 (0.43;1.28)	0.95 (0.48;1.43)	1.15 (0.58;1.73)
SWE	6.18 (3.09;9.26)	7.42 (3.71;11.13)	8.49 (4.24;12.73)	9.34 (4.67;14.01)
THA	2.04(1.02;3.06)	2.47(1.24;3.71)	3.03(1.51;4.54)	3.79(1.90;5.69)
TUR	2.37(1.18;3.55)	2.83(1.42;4.25)	3.32(1.66;4.99)	3.85(1.92;5.77)
TWN	6.83(3.42;10.25)	8.03(4.01;12.04)	8.97(4.48;13.45)	9.52(4.76;14.29)
UKR	2.64(1.32;3.96)	3.89(1.95;5.84)	4.62(2.31;6.93)	5.06(2.53;7.59)
USA	6.67(3.34;10.01)	7.46(3.73;11.18)	8.25(4.12;12.37)	9.03(4.52;13.55)
VNM	1.43(0.72;2.15)	2.23(1.12;3.35)	2.73(1.36;4.09)	3.10(1.55;4.65)
WAF	0.66(0.33;0.99)	0.84(0.42;1.26)	1.07(0.53;1.60)	1.37(0.69;2.06)

ANNEX IV: SSP2 narrative implementation

SSP2 storyline is defined in van Vuuren et al., (2007): “Current trends continue with some progress towards the Millennium Development Goals, lower energy and material intensity consumption and lower fossil fuel dependency. There is an unequal development rate between low income countries and a persistence of global and in-country inequalities. Low level of investment in education prevents low population growth. Global governance achieves an intermediate level of environmental protection”. The demographics, energy and land parameters are described in Riahi et al. (2016).

The air pollutant emission trajectories are based on the default GCAM SSP2 emission factors (hereinafter EF), which are extensively analyzed in Rao et al (2017). The trend of these EFs will be different depending on the GDP of each country:

- High income countries: The air pollutant emissions will be lower than the current levels. The already stablished policy is going to be effectively implemented until 2030, with regionally differentiated trajectories from then on.
- Low income countries: They will need smaller income levels to catch up with the developed world, so the emission control strategies would start earlier than in more developed regions.

In all of the regions (high, medium and low income levels), there is a moderated technological development assumed. The implementation of these parameters into the model and the source database is summarized in Rao et al (2017). The source of each EFs is summarized in the following table:

Table IV-I: Sources of the applied emission factors. Source: Adapted from Rao et al (2017), supplementary material

Source	Activity	Base year.	Source of base year data
End-use energy use (industry, transport, residential, services and other)	Energy consumption	2005	EDGAR 4.2 (BC and OC is from Van Marle et al 2017)
Energy sector (production of power, hydrogen, coal, oil, gas, bioenergy)	Energy production	2005	EDGAR 4.2 (BC and OC is from Van Marle et al 2017)
Other energy conversion	Energy conversion	2005	EDGAR 4.2 (BC and OC is from Van Marle et al 2017)
Emissions from industrial process	Industry value added (IVA)	2005	EDGAR 4.2 (BC and OC is from Van Marle et al 2017)
Cement and Steel	Regional production	2005	EDGAR 4.2 (BC and OC is from Van Marle et al 2017)
Enteric fermentation, cattle	Production of livestock products	2005	EDGAR 4.2
Animal waste, all animal categories	Production of livestock products	2005	EDGAR 4.2
Landfills	Population, GDP	2005	EDGAR 4.2
Deforestation	Size of forest OR change in size of forest	2005	EDGAR 4.2 (BC and OC is from Van Marle et al 2017)
Agricultural waste burning	Agricultural production	2005	EDGAR 4.2 (BC and OC is from Van Marle et al 2017)
Traditional biomass burning	Traditional biomass consumption	2005	EDGAR 4.2 (BC and OC is from Van Marle et al 2017)
Savannah burning	Grassland area	2005	EDGAR 4.2 (BC and OC is from Van Marle et al 2017)
Domestic sewage treatment	Population, GDP	2005	EDGAR 4.2
Wetland rice fields	Rice production	2005	EDGAR 4.2
Crops	Crop production	2005	EDGAR 4.2
Managed grassland			
Indirect emissions			
Land use change			
International Shipping	Energy consumption	2005	EDGAR 4.2 (BC and OC is from Van Marle et al 2017)

Socioeconomic narrative plays an important role in modelling studies. Assumed population will determine activity levels, for example energy consumption, which is central for the estimating emissions levels. Additionally, population is also essential for the calculation of premature deaths associated with a certain level of $PM_{2.5}$ and O_3 concentration. GDP growth will also be a key factor for determining activity levels and also for the calculation of the regional VSL. Emission levels would also vary depending on the EFs applied. In order to capture the potential differences between SSPs, following figures summarize socioeconomic trends and the associated changes in emission projections per narrative.

Additionally, the SSP scenario air pollutant emission factors used in this PhD Thesis are preliminary versions that have been subsequently updated for the official SSP scenario release. The difference in terms of global air pollutant emissions for our central SSP2 cases between the version used in this PhD Thesis and the updated SSP2 emission factors used in Calvin et al. (2017) are presented in Figure IV-III. On a global basis, emissions change very little except for NOx. Given that health co-benefits are dominated by $PM_{2.5}$ emissions, this update will not materially impact the overall conclusions from the developed studies. The slightly larger NOx emissions in the official SSP2 scenario release might result in slightly higher O_3 co-benefits.

Figure IV -I: Socioeconomic factors per SSP scenario

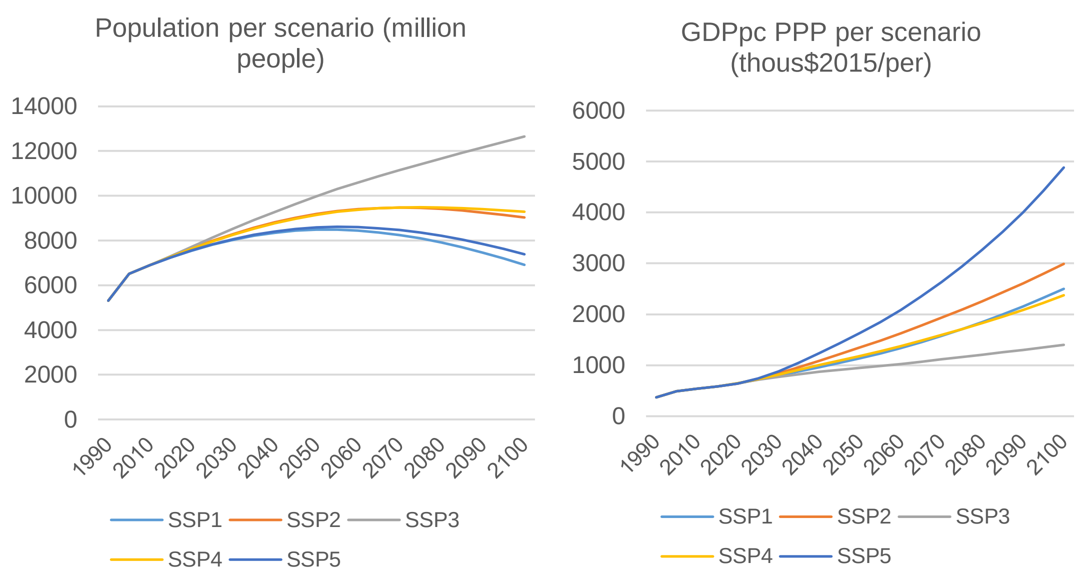


Figure IV -II: Emission trajectories of pollutants per SSP scenario (Tg)

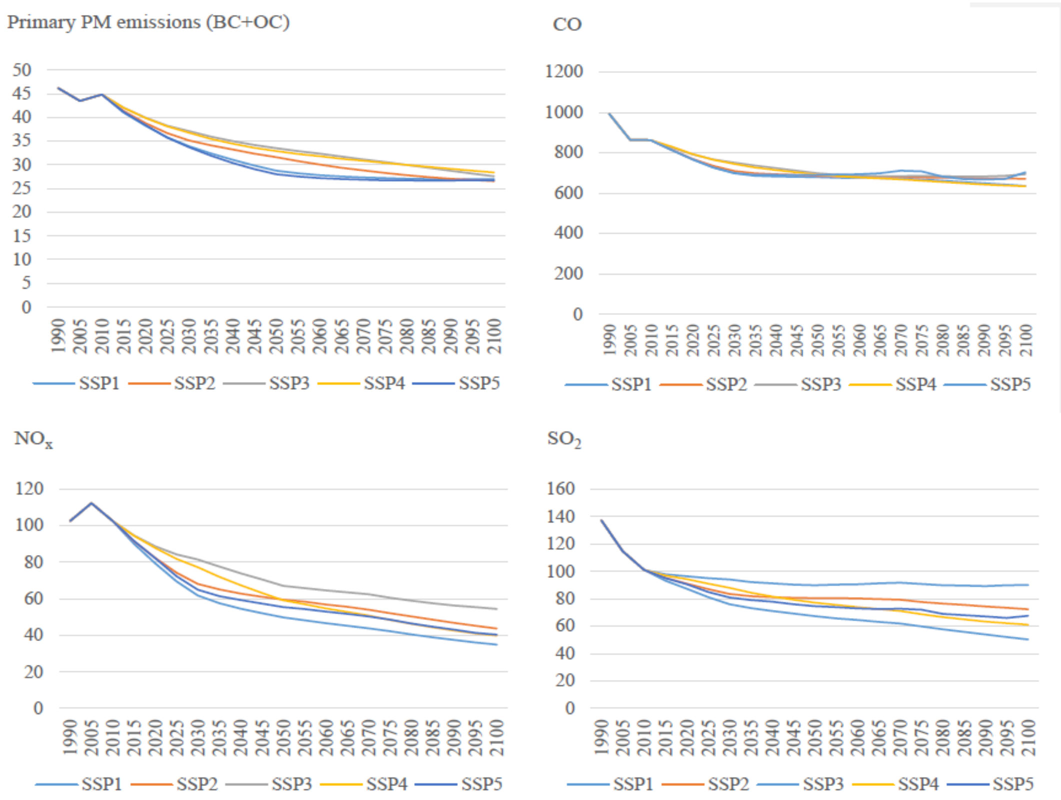
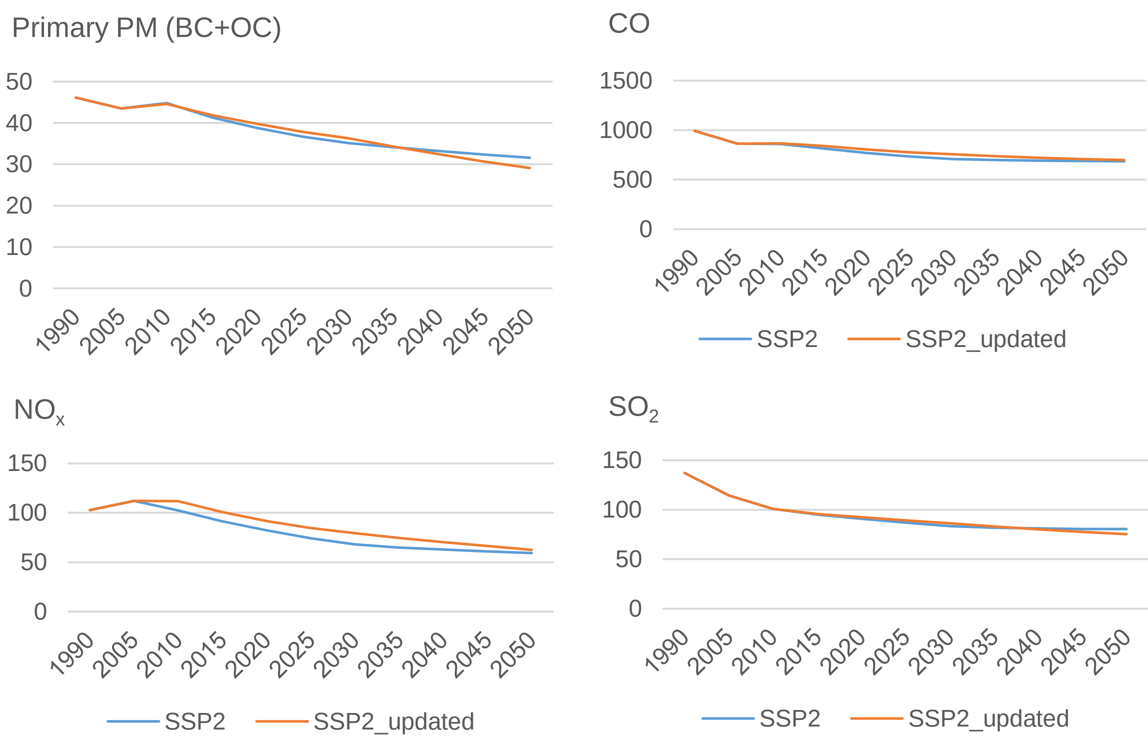


Figure IV -III: Baseline scenario emission trajectories of the used and the updated SSP2 scenarios (Tg)



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