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Global greenhouse gas emission pathways until 2050

Final report

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Global greenhouse gas emission pathways until 2050

Final report

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Abstract

The project “Global greenhouse gas emission pathways until 2050” (2015-2017) aimed to develop transformation scenarios and strategies that both limit global warming to 2°C and take into account a number of environmental and sustainability criteria, such as food security, air quality, protection of aquatic and terrestrial ecosystems as well as socio-economic targets. This report presents the main findings of this work.

The report opens with an assessment of the requirements for limiting future global temperature rise to less than 2°C. It then explores to what extend current climate policies, and especially the Nationally Determined Contributions (NDCs) support or endanger the achievement of the non-climate specific UN sustainable development goals (SDGs) and from here specifically looks at the sustainability impacts of two main climate protection measures, i.e. biomass production and electricity generation from renewables. The report concludes with an assessment of sustainability-oriented strategies using an integrated energy-economy-climate and land-use modelling framework and highlights the potential of comprehensive climate policy approaches that align climate protection with sustainable development goals.

Kurzbeschreibung

Das Projekt " Globale Treibhausgasemissionspfade bis 2050" (2015-2017) hat das Ziel Transformationsszenarien und -strategien zu entwickeln, die sowohl die globale Erwärmung auf 2°C begrenzen als auch eine Reihe von Umwelt- und Nachhaltigkeitskriterien wie Ernährungssicherheit, Luftqualität, Schutz der aquatischen und terrestrischen Ökosysteme sowie sozio- ökonomische Ziele berücksichtigen.

Der vorliegende Bericht stellt die im Projekt erarbeiteten Erkenntnisse und Ergebnisse dar. Er verdeutlicht die Anforderungen für eine Begrenzung des globalen Temperaturanstiegs auf weniger als 2°C. Er zeigt auf inwieweit jetzige Klimapolitiken, und insbesondere die nationalen Klimabeiträgen (NDCs), die Erreichung von nicht klima-spezifischen UN-Nachhaltigkeitsziele (SDGs) unterstützen oder gefährden. Im Bericht wird insbesondere auf die Nachhaltigkeitsauswirkungen zweier wichtiger Klimaschutzmaßnahmen eingegangen, d.h. auf die Produktion von Biomasse und die Erzeugung von Strom aus erneuerbaren Energien. Er schließt mit der Auswertung neuer Szenarien der integrierten Energie-Ökonomie-Landnutzungs-Klima-Modellierung und hebt das Potential umfassender politischer Ansätze, welche Klimaschutz und Nachhaltigkeitsziele miteinander vereinbaren, hervor.

Acknowledgement

The work on sustainable decarbonisation of power supply (Ch. 4) presented in this report partially builds on the results of the EU FP7 project ADVANCE (funding agreement grant number 308329) conducted in parallel to the UBA project “Global greenhouse gas emission pathways until 2050”.

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List of Abbreviations

AR5 IPCC	Fifth Assessment Report
BECCS	bioenergy with carbon dioxide capture and storage
CCS	carbon dioxide capture and storage
CDR	carbon dioxide removal
CO2	carbon dioxide
EJ/yr	exajoules per year
Mha	million hectares
FFI	fossil fuels and industry
GHG	greenhouse gas
GtCO2	gigatonnes of carbon dioxide
IAM	Integrated Assessment Model
INDC	Intended Nationally Determined Contribution
NDC	Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
LU	land-use
SD	Sustainable Development
SDG	Sustainable Development Goals
SO2	sulphur dioxide
tCO2	tonnes of carbon dioxide
UNFCCC	UN Framework Convention on Climate Change

Summary

This report elaborates on the findings of the project “Global greenhouse gas emission pathways until 2050” conducted by the Potsdam Institute for Climate Impact Research (PIK) and the Mercator Research Institute on Global Commons and Climate Change (MCC) and funded by the Federal Environment Agency (UBA) in the years 2015-2017.

The project aimed to develop transformation scenarios and strategies that both limit global warming to 2°C and take into account a number of environmental and sustainability criteria, such as food security, air quality, protection of aquatic and terrestrial ecosystems as well as socio-economic targets. As a first step, the project defined criteria and indicators to assess the sustainability of different climate change mitigation strategies and scenarios. Input from external stakeholders was gathered within a workshop in June 2015 (WP1). The project then applied these criteria for the assessment of existing transformation scenarios (WP2). Strategies taking into account climate and sustainability targets were developed (WP3) and, based on this, a new set of sustainability-oriented scenarios was produced and assessed by using the integrated energy-economy-climate and land-use modelling framework REMIND-MAgPIE (WP4). The results of the work are documented in the five chapters of this report that provide the following key insights:

1) Mitigation challenges for the 1.5°C target

Scenario evidence provided by Integrated Assessment Models (IAMs) sheds light onto the mitigation requirements of the 1.5°C limit. We find that the remaining carbon budget for the 1.5°C limit is close to zero as even most optimistic scenarios show that it will not take longer than 5 years from now to exhaust the remaining carbon budget. The close-to-zero carbon budget of the 1.5°C means that almost all CO2 emissions that are emitted from today onwards will need to be compensated by removing them from the atmosphere through carbon dioxide removal (CDR). What is more, net carbon-neutrality of the global economy will need to be achieved at high speed and no later than between 2045 and 2060. This involves both much faster reductions of CO2 emissions from burning fossil fuels than pledged under the current mitigation action commitments (NDCs), as well as large scale application of carbon dioxide removal. CDR, and most importantly the combination of bioenergy with carbon capture and storage (BECCS), can bear a range of adverse sustainability risks, and its potential is not well-understood at this stage.

2) 2°C and Sustainable Development Goals

Drawing on existing scenario results from a recent energy-economy-climate model inter-comparison project, we analysed synergies and (risk) trade-offs of alternative 2°C pathways across indicators relevant for energy-related SDGs and sustainable energy objectives. We find that the longer the world delays implementing short-term climate policies consistent with the long-term climate goals, and the fewer technologies it is willing to use, the more it lowers the prospects of reaching other SDGs. For example, limiting the availability of key mitigation technologies such as Carbon Capture and Storage (CCS) yields some co-benefits (such as an earlier phase-out of coal) and decreases risks specific to these technologies but greatly increases many others (such as leading to larger capacities of nuclear and bioenergy). Weak and near-term policies broadly in line with current NDCs involve substantial trade-offs and lower synergies across multiple energy-related sustainable development dimensions, especially when combined with constraints on technologies. At the same time, aggressive energy savings can reduce SD risks across the whole spectrum and mark an important component of decarbonisation. Considering the wider SD implications is key to find socially acceptable 2°C mitigation pathways: the prospects of meeting other SDGs need not dwindle and can even be enhanced for some goals if appropriate climate policy choices are made.

3) Trade-offs between large-scale bioenergy production for climate change mitigation and other Sustainable Development Goals

Large-scale bioenergy deployment is a key element of 1.5°C and 2°C transformation pathways. However, the mitigation effect of bioenergy deployment (SDG 13) may come at the cost of adverse side-effects in the land-use sector due to large biomass requirements. Thus large-scale bioenergy deployment may conflict with other SDGs. We analysed such trade-offs under different scenarios of environmental protection and land-sparing measures. We find that a) high levels of bioenergy production can be achieved in 2050 but at significant environmental costs, b) forest or water protection schemes can reduce environmental externalities of bioenergy production substantially, but at the cost of new trade-offs, c) land-sparing measures like improved agricultural productivity or less resource intensive food consumption lower environmental side-effects of bioenergy production without new trade-offs, d) a holistic approach, combining environmental protection with land-sparing measures, to align large-scale bioenergy deployment with the SDG agenda is most promising.

4) Sustainable power sector decarbonisation

Our research shows that the electricity supply sector – and especially renewable energy from wind and solar power – is at the heart of the energy transformation effort for well-below 2°C climate stabilization in line with other environmental sustainability goals. Reaping the high potential for low-cost emission reduction of the power sector at an early stage is essential for climate change mitigation. We find that the sector could be almost fully decarbonized through wind and solar power alone, without the use of nuclear and CCS. This would require, however, considerable additional investments into grid infrastructure and storage systems. We also find that the low-carbon transformation yields substantial environmental co-benefits, which outweigh adverse environmental side-effects. Among alternative decarbonisation pathways, strategies relying heavily on wind and solar are superior to those with substantial CCS and nuclear deployment in terms of minimizing environmental impacts. However, this conclusion only concerns the power sector and disregards emissions that are difficult to reduce in e.g. the transport and agricultural sectors.

5) Sustainability oriented mitigation pathways towards 1.5 and 2°C

Through the analysis of first scenarios on sustainability-oriented decarbonisation pathways in line with the 1.5°C and 2°C warming limits, we find that an integration of different policy interventions, deviating from the least-cost paradigm thus far prevalent in mitigation research reduces risks across a wide range of climate and further sustainability dimensions.

- Direct policy regulation of harmful or risky technology approaches, e.g., biomass use or nuclear power, lowers some environmental impacts but also increases pressures in other sustainability dimensions.
- Similarly, accelerating near-term emission reduction increases the co-benefits of mitigation, and reduces the need for potentially problematic negative emission technologies, but comes at the expense of higher mitigation costs in the near-term.
- Shifts to more sustainable lifestyles, e.g. less energy- and material-intensive consumption patterns as well as less meat-intensive diets, yield across-the-board sustainability improvements and help to mitigate trade-offs between sustainability targets. The combination of these three approaches balances the risks in the various dimensions, and, as most of the effects are complementary leads to the lowest sustainability risks in most dimensions.

Furthermore, we find that the more ambitious 1.5°C target increases both co-benefits of climate action compared to 2°C, but also exacerbates some sustainability risks connected to crucial mitigation technologies, such as biomass and CCS, and also increases economic pressures.

The analysis highlights the benefit of considering a range of sustainability dimensions, both when it comes to deciding on the right balance of policy approaches and when considering different long-term climate targets.

Zusammenfassung

Dieser Bericht stellt die Ergebnisse des Projekts "Globale Treibhausgasemissionspfade bis 2050" dar. Das Projekt ist ein gemeinsames Vorhaben des Potsdam-Instituts für Klimafolgenforschung (PIK) und des Mercator Research Institute on Global Commons and Climate Change (MCC) und wurde durch das Umweltbundesamt (UBA) in den Jahren 2015-2017 gefördert.

Das Projekt hat das Ziel Transformationsszenarien und -strategien zu entwickeln, die sowohl die globale Erwärmung auf 2 °C begrenzen als auch eine Reihe von Umwelt- und Nachhaltigkeitskriterien wie Ernährungssicherheit, Luftqualität, Schutz der aquatischen und terrestrischen Ökosysteme sowie sozio- ökonomische Ziele berücksichtigen. In einem ersten Schritt wurden Kriterien und Indikatoren zur Bewertung der Nachhaltigkeit von Transformationsszenarien und -strategien formuliert. Dies erfolgte unter Einbeziehung externer Stakeholder innerhalb eines Workshops im Juni 2015 (WP1). Diese Kriterien wurden dann einer umfassenden Bewertung der aktuellen Szenarienliteratur zu Grunde gelegt, bei der bestehende Klimaschutzszenarien auf ihre Nachhaltigkeit und Umweltwirkungen hin untersucht wurden (WP2). Aufbauend auf den gewonnenen Erkenntnissen, wurden Strategien erarbeitet, um vielfältige Nachhaltigkeitsziele gleichermaßen zu erreichen. Unter Berücksichtigung der Klima- und Nachhaltigkeitsziele wurden Strategien entwickelt (WP3) und durch die integrierte Energie-Ökonomie-Landnutzungs-Klima-Modellierung mit den Modellen REMIND und MAgPIE ausgearbeitet (WP4). Die Ergebnisse dieser Arbeit werden in den fünf Kapiteln dieses Berichts dokumentiert und können folgendermaßen zusammengefasst werden:

1) Herausforderungen einer Emissionsminderung zur Erreichung des 1.5 ° C Ziels

Szenarien der integrierten Energie-Ökonomie-Landnutzungs-Klima-Modellierung bringen Licht in die Anforderungen einer für das 1.5 ° C Ziel notwendigen Emissionsminderung. Die im Projekt durchgeführten Arbeiten zeigen, dass das verbleibende CO2-Budget zur Erreichung dieses Zieles nahe Null ist. Selbst in optimistischen Szenarien ist das noch verbleibende CO2-Budget in maximal 5 Jahren aufgebraucht. Das begrenzte CO2-Budegt hat zur Folge dass fast alle ab heute generierten CO2-Emissionen durch das künstliche Entfernen von CO2 aus der Atmosphäre (Carbon Dioxide Removal genannt, kurz CDR) kompensiert werden müssen. Darüber hinaus muss die Kohlenstoffneutralität der Weltwirtschaft mit hoher Geschwindigkeit und spätestens zwischen 2045 und 2060 erreicht werden. Dies geht mit einer deutlich schnelleren Reduktion der CO2-Emissionen aus der Nutzung fossiler Energieträger einher, als durch die nationalen Verpflichtungen zur Minderung von Treibhausgasen (nationale Klimabeiträgen - NDCs) vorgesehen. Außerdem wird der Einsatz in großem Maßstab von CDR erforderlich. CDR, vor allem die Kombination von Bioenergie mit Kohlenstoffabscheidung und -lagerung (BECCS), birgt eine Reihe von nachteiligen Nachhaltigkeitsrisiken. Außerdem ist das zur Verfügung stehende Potenzial derzeit noch weitgehenden unbekannt.

2) Das 2°C-Ziel und die UN-Nachhaltigkeitsziele (SDGs)

Auf der Grundlage aktueller Szenarienergebnisse einer kürzlich durchgeführten Modellvergleichsstudie wurden Synergien und Zielkonflikte alternativer 2°C-Pfade durch energiebezogene Nachhaltigkeitsindikatoren analysiert. Unsere Analyse zeigt, dass eine verspätete Umsetzung kurzfristiger, mit langfristen Klimazielen vereinbarer Klimapolitik sowie eine eingeschränkte Technologienutzung die Erreichung der SDGs gefährden.

Zum Beispiel hat die begrenzte Verfügbarkeit von Schlüsseltechnologien wie u.a. Kohlenstoffabscheidung und –speicherung (CCS) positive Nebeneffekte (wie zum Beispiel ein zeitnaher Kohleausstieg) und kann Technologie-spezifische Risiken verringern. Dennoch erhöhen sich Risiken (wie zum Beispiel eine Erhöhung der Atomkraft- und Bioenergiekapazitäten) insgesamt und über alle SDGs hinweg. Eine schwache und kurzfriste Klimapolitik wie durch die NDCs festgelegt führt zu wesentlichen Zielkonflikten und verringert Synergien über mehrere energiebezogene Nachhaltigkeitsdimensionen hinweg, insbesondere in Verbindung mit Technologieeinschränkungen. Gleichzeitig können massive

Energieeinsparungen Nachhaltigkeitsrisiken insgesamt verringern und maßgeblich zur Dekarbonisierung beitragen. Überlegungen zu Nachhaltigkeitsimplikationen sind von zentraler Bedeutung für die Bestimmung sozialverträglicher 2°C-Pfade: die Aussichten die SDGs zu erreichen müssen nicht schwinden und können sogar für einige Ziele, mit den entsprechenden klimapolitischen Entscheidungen, verbessert werden.

3) Zielkonflikte zwischen großflächiger Bioenergieproduktion für den Klimaschutz und anderen Nachhaltigkeitszielen (SDGs)

Großflächige Bioenergienutzung ist ein Schlüsselelement aller 1.5°C und 2°C Transformationspfade. Aber der Klimaschutzeffekt von Bioenergienutzung (SDG 13) könnte mit negativen Folgen für das Landnutzungssystem aufgrund der hohen Nachfrage nach Biomasse einhergehen. Daher könnte eine hohe Bioenergienutzung mit anderen Nachhaltigkeitszielen in Konflikt stehen. Wir haben solche Zielkonflikte im Zusammenhang mit Umweltschutzmaßnahmen und Maßnahmen, die den Druck im Landnutzungssystem verringern, analysiert und können hieraus schlussfolgern, dass a) hohe Bioenergieproduktion im Jahr 2050 erreicht werden kann, aber mit erheblichen Umweltkosten einhergeht, b) Wald- oder Wasserschutzsysteme Umweltexternalitäten der Bioenergieproduktion erheblich reduzieren, aber hierdurch neue Zielkonflikte entstehen können, c) druckreduzierende Maßnahmen, wie eine verbesserte landwirtschaftliche Produktivität oder eine Senkung des ressourcenintensiven Nahrungsmittelverbrauchs, Umweltfolgen der Bioenergieproduktion verringern kann ohne neue Zielkonflikte zu erzeugen, d) ein ganzheitlicher Ansatz, der Umweltschutz mit druckreduzierenden Maßnahmen kombiniert, am vielversprechendsten erscheint um großflächige Bioenergieproduktion mit der SDG-Agenda zu vereinbaren.

4) Nachhaltige Dekarbonisierung des Energiesektors

Unsere Forschung zeigt, dass der Stromversorgungssektor, und vor allem Stromerzeugung aus erneuerbare Energiequellen wie Wind- und Sonne, maßgeblich für eine Energiewende ist, die eine Klimastabilisierung unter 2°C mit der Erreichung anderer ökologische Nachhaltigkeitsziele in Einklang bringen will. Wichtig ist für den Klimaschutz, dass das Potenzial für eine kostengünstige Emissionsreduktion des Energieversorgungssektors in einem frühen Stadium ausgeschöpft wird. Unsere Analyse zeigt, dass der Stromsektor durch Wind- und Solarenergie allein und ohne Verwendung von Kernenergie und Kohlenstoffabscheidung und -lagerung (CCS) fast vollständig dekarbonisiert werden könnte. Dies erfordert jedoch erhebliche zusätzliche Investitionen in Netzinfrastruktur und Speichersysteme. Unsere Analyse zeigt außerdem, dass eine Transformation zu einer kohlenstoffarmen Gesellschaft erhebliche Vorteile für die Umwelt aufweist und negative Umwelteinflüsse aufwiegt. In Hinblick auf die Minimierung der Umweltauswirkungen, sind Emissionsminderungsstrategien die verstärkt auf Wind- und Solarenergie setzen, denen mit erheblichem Einsatz von CCS und Kernenergie überlegen. Diese Schlussfolgerung betrifft den Stromversorgungssektor und trägt nicht den schwer reduzierbaren Treibhausgasemissionen anderer Sektoren wie etwa Transport und Landwirtschaft Rechnung.

5) Nachhaltige Vermeidungspfade für 1.5-2°C

Eine Auswertung der im Projekt erzeugten Nachhaltigkeits- und Klimaschutzszenarien weist auf die möglichen Vorteile einer breiten Integration unterschiedlicher Politikmaßnahmen hin. In Abweichung vom weit verbreiten Paradigma der Kostenminimierung zeigt unsere Analyse, dass die Integration unterschiedlicher Politikmaßnahmen Risiken in einem breiten Spektrum an Klima und Nachhaltigkeitsdimensionen abschwächt. Insbesondere lässt unsere Analyse folgende Schlussfolgerungen zu:

- Die direkte politische Regulierung von schädlichen oder risikohaften Technologieansätzen, z. B. die Nutzung von Biomasse oder Kernenergie, verringert einige Umweltauswirkungen, erhöht aber auch den Druck in den anderen Nachhaltigkeitsdimensionen.
- In ähnlicher Weise erhöht schnellere kurzfristige Emissionsreduktion die positiven Nebenwirkungen von Emissionsvermeidung, hat allerdings den Nachteil dass dadurch auch die kurzfristigen Vermeidungskosten im Energiesystem ansteigen.

- Der Übergang zu nachhaltigeren Lebensstilen, durch z.B. weniger energie- und materialintensive Konsummuster sowie weniger fleischhaltige Diäten, sorgt für eine verbesserte Nachhaltigkeitsbilanz und hilft die Zielkonflikte zwischen Nachhaltigkeitszielen abzuschwächen.
- Die Kombination der drei obigen Ansätze balanciert so die Risiken in den unterschiedlichen Dimensionen aus, und führt in den meisten Indikatoren zu den niedrigsten Risikowerten, da die Ansätze teilweise komplementär wirken.
- Das 1.5°C-Ziel stärkt im Vergleich zum 2°C-Ziel zusätzlich die positiven Nebenwirkungen des Klimaschutz, verschärft aber auch einige nachhaltigkeitsbezogenen Risiken die mit entscheidenden Vermeidungstechnologien zusammenhängen, so wie Biomasse mit CCS. Zudem steigen die ökonomischen Vermeidungskosten.

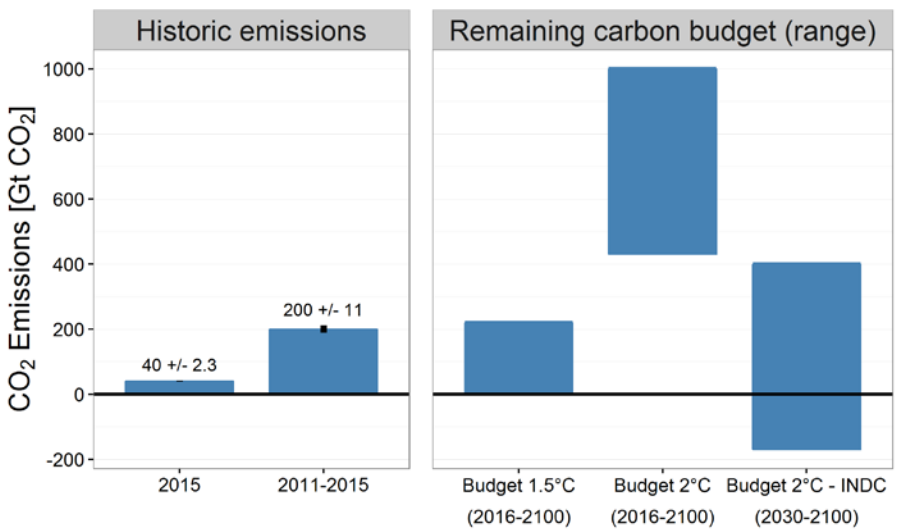
Die Analyse betont den Nutzen einer breiten Analyse vielfältiger Nachhaltigkeitsdimensionen, die sowohl bei der Wahl der Kombination an Politikansätzen als auch bei der Evaluation unterschiedlicher langfristiger Klimaziele wertvolle Erkenntnisse bietet.

1 Mitigation challenges for the 1.5°C target

The explicit reference to the aim of "pursuing efforts to limit the temperature increase to 1.5°C" in the Paris Agreement (UNFCCC 2015a) has revived the political and scientific interest in this very low stabilization target. In this chapter we summarize the available scientific evidence on the mitigation requirements of the 1.5°C limit and how they differ from the 2°C limit, in particular in terms of technology deployment needs, near-term policy requirements and cost implications. The scientific evidence on the 1.5°C limit is scarce. Only two Integrated Assessment Models have so far provided comprehensive scenario evidence that has been published in the peer-reviewed literature. We distil the main insights from these scenarios on the implications of the 1.5°C limit as discussed in Luderer et al. (2013), Rogelj et al. (2013; 2013b; 2015) and Clarke et al. (2014).

1) The remaining carbon budget for the 1.5°C limit is close to zero: The Fifth IPCC Synthesis report (AR5) emphasized that the remaining amount of carbon that can still be released to the atmosphere (carbon budget) for keeping a particular temperature target is fixed (IPCC 2014a). In Figure 1 we present the budget ranges that have been estimated for the 1.5°C and 2°C targets. Limiting warming to below 2°C with a greater than two thirds likelihood constrains the remaining CO2 emissions to no more than 1,000 GtCO2 from 2016 until the end of the century (IPCC 2014a). For the 1.5°C limit the remaining budget might already be fully exhausted. Even if we focus on the upper limit of the budget, it will not take longer than 5 years from now to exhaust this remaining budget of 200 GtCO2, given that current emissions amount to 40 GtCO2 per year. If countries deliver only on the emission reductions promised in the Intended Nationally Determined Contributions (INDC) without substantially ratcheting up short-term ambition, the 2°C budget will be close to exhaustion in 2030 – similar to the 1.5°C budget today.

Figure 1 Recent CO2 emissions and carbon budget ranges for the 1.5°C and 2°C limits. The left panel shows historic CO2 emission estimates derived from Le Quéré et al. (2016). The right panel shows carbon budget ranges found in the scientific literature for the 1.5°C (Rogelj et al. 2015) and the 2°C (IPCC 2014a) limits. Ranges reflect carbon cycle uncertainties as well as the breadth of alternative pathways with differences in mixture of greenhouse gases and the timing of their release. Budget 2°C-INDC gives the budget range for the period 2030-2100 after subtracting the estimated CO2 emission releases 2011-2030 implied by the Intended National Determined Contributions (INDCs) derived from Den Elzen et al. (2015). Own illustration by PIK.



2) The 1.5°C limit fundamentally depends on the large-scale availability of carbon dioxide removal (CDR) technologies: The close-to-zero carbon budget of the 1.5°C means that almost all CO_2 emissions that are emitted from today onwards will need to be compensated for later in the 21st century by removing them from the atmosphere through CDR (see Box 1) with all the given uncertainties about carbon cycle dynamics this involves. The 1.5°C limit will therefore require, at the very least, a removal of 500 $GtCO_2$ (or about 10-15 years of CO_2 emissions at current rates) from the atmosphere, or negative emissions until the end of the 21st century – but probably much more. The larger carbon budget of the 2°C limit means that there would be considerably more freedom in technology choice. In fact, aggressive, immediate mitigation efforts still offer a slim chance of keeping warming below 2°C without any reliance on CDR technologies – obviously at higher costs, however. But the window of opportunity to limit the dependence on CDR is closing rapidly: emission reductions in line with the current INDCs imply a similar dependency on CDR in 2030 for the 2°C limit as we see it for 1.5°C today. Hence, any further delay in substantial and sustained global emission reduction essentially means extending the political bet on the large-scale availability of CDR technologies from the 1.5°C to the 2°C limit.

Carbon Dioxide Removal (CDR) Technologies

CDR technologies aim to remove carbon dioxide (CO_2), a major driver of climate change, from the atmosphere. They include relatively simple options like planting more trees to lock up CO_2 as they grow (afforestation), or crushing rocks that naturally absorb CO_2 and spreading them on soils so that they remove CO_2 more rapidly (terrestrial enhanced weathering). Other higher-tech options include using chemicals to absorb CO_2 from the air (air capture), or burning plants for energy and capturing the CO_2 that would otherwise be released, then storing it permanently deep below the ground, called bioenergy with carbon capture and storage (BECCS).

New research (Smith et al. 2016) has started to consider some of the impacts of negative emission technologies on land use, greenhouse gas emissions, water use, the earth's reflectivity, and soil nutrient depletion, as well as the energy and cost requirements for each technology. The study shows that there are many such impacts that vary across technologies. Some are costly and require a lot of additional energy, while others are much cheaper but come with very large land requirements. Most of these impacts are scale-dependent and not sufficiently understood. They will need to be satisfactorily addressed if negative emission technologies are to play a significant role in achieving climate change targets.

3) 1.5°C pathways require an even faster energy system decarbonisation: 1.5°C-consistent transformation pathways resemble pathways for the 2°C limit in many respects, but they combine their most challenging features: they do not allow for any further delay in strong and sustained global GHG emissions reductions, require a broad portfolio of mitigation technologies including the large-scale availability of CDR technologies, and are highly dependent on aggressive energy demand reduction strategies. These add up to an even faster pace of decarbonisation for 1.5°C pathways: major milestones are typically achieved 10-20 years earlier than in 2°C pathways. For instance, 1.5°C pathways reach net carbon neutrality between 2045 and 2060, compared to 2050-2080 in typical 2°C pathways. The institutional and political difficulties in managing such a swift transition to carbon-neutrality across all sectors of the economy cannot be underestimated.

4) The window for 1.5°C closes rapidly: Most of the 1.5°C scenarios documented in the literature assume an immediate onset of comprehensive climate policies. Only a small subset of 1.5°C scenarios consider the effects of the Cancun pledges on 2020 emission levels, while the others feature 2020 emissions that are substantially below those implied by the INDCs. For 2030, the 1.5°C scenarios explored in Rogelj et al. (2015) feature greenhouse gas emission levels of around 25-35 $GtCO_2e$, much lower than the 53-59 $GtCO_2e$ estimated as the aggregate effect of the INDCs (UNFCCC 2015b). This shows that currently planned climate policies are woefully inadequate for the 1.5°C target. In fact, current policy trends endanger not only the 1.5°C but also the 2°C limit. In terms of the implied economic mitigation challenges, staying below the 2°C limit after following INDCs until 2030 is comparable to limiting global warming to 1.5°C from current emission levels (Luderer et al. 2013).

5) The wider sustainability implications of 1.5°C scenarios are not well understood: Recent research shows that alternative mitigation pathways consistent with the 2°C target can have very substantial sustainable development implications. Trade-offs with other sustainable development targets increase as the remaining carbon budget decreases and the ability to manage these trade-offs fades away (Stechow et al. 2016). These challenges are expected to be exacerbated for the 1.5°C target. In particular, there are strong concerns regarding the adverse sustainability impacts of a large-scale application of CDR technologies. While these adverse impacts could considerably offset the benefits from less warming, there is no comprehensive evidence available thus far to inform this discussion adequately.

The 1.5 and 2°C targets in the scenario literature

There is a high degree of ambiguity in the operationalization of climate targets such as the 1.5 and 2°C limits. In climate change mitigation scenario studies, the objective of holding the increase of global mean temperature to below 2°C limit is typically interpreted as a not-to-exceed target, i.e. emission constraints are formulated such that the global mean temperature stays below 2°C throughout the 21st century with a certain probability. This is in line with the formulation in the Copenhagen Accord that the “increase in global temperature should be below 2°C” (UNFCCC 2009). As summarized in the IPCC’s Fifth Assessment Report, several scenario studies, many of which are based on multiple integrated assessment models, have shown the achievability of the 2°C objective with medium (50-66%) or high (>66%) likelihood.

Given the warming commitment from historic emissions as well as the additional unavoidable near-term emissions that would occur even if the world initiated the transition to carbon-free economy immediately, it is no longer possible to avoid an overshoot of the 1.5°C threshold, however. Therefore, Rogelj et al. (2015) categorized pathways as 1.5°C-consistent if they return to below 1.5°C with an above 50% likelihood by 2100. The few 1.5°C-consistent pathways available from the scientific literature typically peak at 1.6-1.8°C, and rely heavily on net negative CO_2 emissions during the 2nd half of the century to return warming to below 1.5°C by 2100.

2 2 °C and Sustainable Development Goals: United they stand, divided they fall?

In the year 2015, two important international agreements were adopted: the United Nations (UN) Sustainable Development Goals (SDGs) and the 'Paris Agreement' under the UN Framework Convention on Climate Change (UNFCCC). The sustainability and climate agendas are highly interrelated: the Paris Agreement frames climate change mitigation in the context of sustainable development (SD), while taking urgent climate action features as one of the SDGs. However, quantification of this relationship has so far been rather limited and focused on a small number of synergies and trade-offs across climate change mitigation and other sustainable energy objectives (Stechow et al. 2016).

Based on existing mitigation scenarios from global integrated energy-economy-climate models (see box on methods), we quantify the interlinkages between different climate change mitigation pathways to keep global mean temperature below 2°C and their performance in other sustainability dimensions (Stechow et al. 2016). We argue that the 2°C goal and the SDGs are two sides of the same sustainability coin: On the one hand, the way the international community addresses the climate problem strongly affects the prospects of achieving other SDGs. On the other, the associated SD risks largely determine which 2°C pathways will be socially acceptable.

If we want to achieve all SDGs, we need a better understanding of how our policy choices today affect outcomes in the future. This analysis aims at making such synergies and trade-offs across mitigation and SDGs more transparent to decision makers. By assessing the risks of various 2°C pathways rather than categorically excluding certain options, it aims at advancing a public debate on socially acceptable climate policy choices. Drawing on existing literature, we calculate impacts of alternative 2°C pathways based on SD risk indicators relevant for ten SDGs and other sustainable energy objectives (see box on methods). More detailed information is provided in the full paper (provided in Annex 1 & 2) that was published as an earlier product within this project.

Main conclusion: For all analysed SD risks, the results consistently showed: the longer the world delays implementing ambitious climate policy, and the fewer technologies it is willing to use, the more it lowers the prospects of reaching other SDGs (see Figure 2). At the same time, aggressive energy savings can reduce SD risks across the whole spectrum and mark an important component of decarbonisation:

1) Fewer synergies and substantial trade-offs across SDGs are locked into the system for weak short-term climate policies that broadly reflect current Intended Nationally Determined Contributions (INDCs). Higher SD risks can be seen in virtually all other sustainability dimensions we considered. These are particularly severe for those related to economic growth, energy access, coal job preservation, food security and resilient grid infrastructure. Constraining technologies and delaying climate action thereby reinforce each other. For instance, delayed 2°C pathways with a limited global bioenergy potential result in extremely high risks to socioeconomic SDGs. Delayed action thus greatly increases the dependence on risky technologies.

Figure 2 Percentage changes in SD risk dimensions that can be linked to a set of SDGs and other sustainable energy objectives in constrained 2 °C pathways relative to optimal pathways (assuming immediate mitigation with full availability of mitigation technologies and conventional energy demand growth). The different shapes denote different short-term climate policy stringencies while the different colours denote different technology cases (see table 3). As the figure aims at showing trends in synergies and risk trade-offs of alternative clusters of 2 °C pathways rather than an exact quantitative analysis, results are plotted in logarithmic scale. Illustration derived from Stechow et al. (2016).

2) Aggressive energy saving can reduce SD risks substantially: As each unit of energy not produced is free of pervasive supply-side risks, reducing energy demand by promoting energy efficiency in end-use sectors (e.g. consumer appliances), lifestyle changes (e.g. people living in higher density areas and eating less dairy and meat) and structural changes in the economy (e.g. shifting to more service-oriented economies) is an essential ingredient of decarbonisation from a SD perspective. An about 50% increase in annual energy efficiency improvements would decrease our dependence on contested technologies such as CCS and nuclear power roughly by a third. Even short-term economic impacts would be significantly less severe and food security would be less threatened. Aiming at more radical energy efficiency improvements across all sectors and rethinking high energy lifestyles seems necessary if trade-offs across SDGs should be kept manageable in a world that is characterized by multiple constraints.

3) Limiting the availability of key mitigation technologies yields some co-benefits but greatly increases many SD risks: If key mitigation technologies are constrained, countries need to achieve even faster near-term emission reductions to stay below 2°C. This results in greater co-benefits in terms of air quality, energy security and lower ocean acidification. At the same time, the required energy system transformation has to increasingly rely on other risky technologies, with higher associated impacts. For instance:

- Unavailability of carbon capture and storage (CCS) results in higher nuclear capacity with associated proliferation risks, higher bioenergy demand with associated risks for food security and biodiversity, and higher energy prices – putting universal energy access at risk.
- Constraining bioenergy availability to 100 EJ per year globally would avoid the worst outcomes in terms of food security and biodiversity risks and slightly reduce CO2 storage as less biomass feedstock could be used to combine bioenergy conversion with CCS. Some other SD risks would, however, still increase.
- Phasing out nuclear energy globally or limiting the solar and wind potential to 20% of regional electricity supply also imply SD risk increases but the magnitude of the effects is much smaller. To stay below 2°C, however, more CCS deployment would be required and foregoing nuclear capacity build-up would require even faster upscaling of renewables.

Climate and sustainability policies cannot be separated from each other any longer. Climate policy not only needs to protect the climate, but should also take SD considerations into account in how it protects the climate. Slowing global energy demand growth and raising short-term ambition beyond the contributions each country has pledged in connection to the Paris Agreement not only improves the chances of staying below 2°C, but also the prospect of reaching other SDGs.

Selection of 2°C pathways and SD indicators in von Stechow et al. (2016)

Selection of 2°C pathways: Tracking SD effects of alternative mitigation pathways across different integrated assessment models is made difficult by heterogeneous input assumptions. To avoid this, data from work package 2 of the model inter-comparison project AMPERE was chosen that harmonized future socio-economic drivers of SD in baseline scenarios, e.g., regional level gross domestic product, population and energy demand growth. It is publicly available (secure.iiasa.ac.at/webapps/ene/AMPEREDB), consistently defines alternative short-term climate policy pathways and combines these with constraints to the availability of key mitigation technologies (Riahi et al. 2013).

Selection of indicators: Building on previous work analysing mitigation scenarios along multiple criteria (Luderer et al. 2013), indicators calculated from integrated model variables were chosen such that they link to SD risk dimensions as well as SDGs and other sustainable energy objectives (see table 1). Due to the limited data availability, the analysis did not address all relevant SDGs explicitly, but many indicators are also relevant for some cross-cutting SDGs, such as poverty and inequality.

As the analysis was based on existing multi-model scenario data not specifically developed for this purpose, it is all the more important to improve existing modelling tools to better address the important questions around the interaction of climate change mitigation (SDG13) and other SDGs.

Table 1 Selection of indicators (Stechow et al. 2016).

Indicators calculated from integrated assessment model variables	SD risk dimensions affected	SDG and sustainable energy objectives
Biomass supply for energy per year	Bioenergy expansion	Food security (SDG 2)
Cumulative BC and SO2 emissions	Air pollutant concentration	Health via air quality (SDG 3.9)
Maximum decadal energy price growth	Energy price growth	Energy access (SDG 7)
Maximum decadal growth reduction	Consumption growth reduction	Economic growth (SDG 8.1)
Idle coal capacity per year	Stranded fossil investment	Full employment (SDG 8.3)
Maximum decadal PV and Wind upscaling	Wind & PV grid integration	Resilient infrastructure (SDG 9)
Cumulative global oil trade, cumulative oil extraction, fuel diversity of transport sector	Oil insecurity, transport sector reliance on oil	Ensure energy security[1]
Nuclear capacity expansion in Newcomers[2]	Nuclear proliferation	Peaceful use of nuclear power
CumulativeCO2 emissions until mid-century	Peak atmosphericCO2 concentration	Minimize ocean acidification (SDG 14.3)
CO2 captured and stored per year	Environmental risks of CCS	Sustainable production (SDG 12.4)

[1] Due to the focus on global risks, the analysis is limited to oil security—the fuel with the highest scarcity concerns and high import dependence in most countries, lacking substitutes in transport (see SI section 3.1.7).

[2] We designed a new indicator that can draw on existing model variables (see SI section 3.2).

3 Trade-offs between large-scale bioenergy production for climate change mitigation and other Sustainable Development Goals

Large-scale bioenergy deployment of up to 300 EJ/yr by 2100 is a key element of 1.5°C and 2°C transformation pathways (Rogelj et al. 2015), primarily in combination with carbon capture and storage (CCS) (Rose et al. 2013). Like the production of food, the production of bioenergy requires land, water and nutrients. Thus, bioenergy cultivation for climate change mitigation in addition to the provision of food for a growing world population might exacerbate adverse side-effects of agricultural production in the coming decades, which would conflict with the newly developed Sustainable Development Goals (SDGs) (United Nations General Assembly 2015).

One approach to reconcile global large-scale bioenergy production with the broader SDG agenda are environmental protection measures such as forest or water conservation schemes (Bonsch et al. 2014; Calvin et al. 2014; Kraxner et al. 2013). However, regulating one environmental externality of bioenergy cultivation may interfere with other SDGs (Nilsson et al. 2016; Smith et al. 2013). For instance, forest protection may increase competition for land, potentially leading to a rise in food prices. Thus, some environmental protection measures may only shift adverse side-effects into another domain.

Another strategy to align large-scale bioenergy production with the broader SDG agenda could be the implementation of measures, which reduce the pressure on land in general (land-sparing measures) such as improved agricultural productivity (Tilman et al. 2011) or reduced consumption of resource intensive livestock products combined with less household waste (Röös et al. 2017; Smith et al. 2013).

This chapter summarizes the outcomes of a study conducted within this project by Humpenöder and Popp et al (for more information see peer-reviewed publication in Annex 3 & 4) where a global land-use model (MAgPIE) (Popp et al. 2014b) has been applied to assess how global large-scale bioenergy crop cultivation for climate change mitigation [SDGs 7, 13] may conflict with other SDGs throughout the 21st century under different scenarios of environmental protection and land-sparing measures (Table 1). In this study various scenarios with identical bioenergy demand (133 EJ in 2050, 300 EJ in 2100) (except a baseline scenario without bioenergy demand) have been assessed to identify the effect of a single measure or a combination of measures on different sustainability indicators. To identify sustainability trade-offs, a multi-criteria analysis has been carried out covering the following indicators, which serve as proxies for the respective SDG in brackets.

- loss of natural land [SDG 15]
- nitrogen losses to the environment [SDGs 13, 14, 15]
- water withdrawals exceeding environmental flow requirements [SDG 14]
- CO2 emissions from land-use change [SDG 13]
- food price index[3] [SDG 2]

Key insights

1) High levels of bioenergy production can be achieved in 2050, but at significant environmental costs: Globally, the production of 133 EJ bioenergy in 2050 requires 311 Mha cropland (global cropland in 2010 is 1581 Mha). In addition, cropland requirements for food/feed production are slightly higher under bioenergy deployment due to competition for the most productive areas. In total, cropland for food, feed and bioenergy expands by 707 Mha between 2010 and 2050 under bioenergy deployment (*Bio* scenario) compared to 326 Mha in the absence of bioenergy (*NoBio* scenario).

[3] The food price index used here weights current food prices based on current food baskets (Paasche price index). For calculating the food price index, we derive so-called shadow prices from the MAgPIE model, which reflect the marginal increase in agricultural production costs for one additional unit of food commodities. In the context of this study, the food price index provides information about the relative impacts on food price development under different bioenergy scenarios.

Cropland mainly expands into pasture and forest areas. Global pasture/forest area (2994/4157 Mha in 2010) declines between 2010 and 2050 by 411/212 Mha under bioenergy deployment (*Bio* scenario) compared to 219/72 Mha without (*NoBio* scenario). Cropland expansion into pasture, forest and other natural vegetation for food, feed and bioenergy production results in global cumulative emissions of 216 Gt CO2 between 2010 and 2050 (*Bio* scenario), compared to 72 Gt CO2 without bioenergy (Figure 3). Thus, the impact of providing 133 EJ bioenergy in 2050 is a tripling of global CO2 emissions from land-use change. In addition, bioenergy deployment raises nitrogen losses due to increased fertilizer use by 16% and unsustainable water withdrawals for irrigation by 47% (*Bio vs. NoBio* scenario in 2050).

2) Forest or water protection schemes can reduce environmental externalities of bioenergy production substantially - but in some cases new trade-offs emerge: If bioenergy production is accompanied by a forest protection scheme, CO2 emissions from land-use change are substantially lower compared to the case without forest protection (*Bio-REDD* vs. *Bio* scenario). However, unsustainable water withdrawals as well as the food price index rise more strongly as a consequence of reduced availability for land expansion under forest protection. Such new trade-offs between bioenergy deployment and other sustainability dimensions also occur (to a limited extent) under a water protection scheme (*Bio-WaterProt* vs. *Bio* scenario). In this case, CO2 emissions from land-use change and the food price index are slightly higher because reduced water availability for irrigation results in more land expansion and increases competition for productive land.

3) Land-sparing measures like improved agricultural productivity or less resource intensive food consumption lower environmental side-effects of bioenergy production without new trade-offs: Higher crop yields along with increased livestock productivity reduce cropland expansion for food and bioenergy production into forests and other natural ecosystems by about 50% (*Bio-IntensAg* vs. *Bio* scenario). As a consequence, CO2 emissions from land-use change are at a similar level as under explicit forest protection (Figure 3). At the same time, the food price index is similarly low as under no bioenergy production because of higher flexibility with respect to satisfying rising food demand. Besides intensification on the supply side, also behavioural changes on the consumer side are considered as land-sparing measures (Smith et al. 2013). Less resource intensive food consumption (*Bio-DemiDiet* scenario) frees-up cropland that is subsequently used for the expansion of bioenergy crops. Hence, forests and other natural ecosystems are only slightly impaired by bioenergy cultivation, also avoiding most CO2 emissions from land-use change and substantially reducing nitrogen losses. At the same time, the food price index is as low as without bioenergy production, as a result of reduced competition for land. Thus, consumer behaviour is a powerful lever to address environmental side-effects of bioenergy crop cultivation without involving new trade-offs.

4) A holistic approach, combining environmental protection with land-sparing measures, to align large-scale bioenergy deployment with the SDG agenda is most promising: Our analysis indicates that no single environmental protection or land-sparing measure can alleviate the various adverse side-effects of large-scale bioenergy production simultaneously (Figure 3). Combining all environmental protection and land-sparing measures considered in our study reduces environmental and social externalities of large-scale bioenergy production most comprehensively (*Bio-All* scenario). CO2 emissions from land-use change are close to zero, nitrogen losses are halved compared to a scenario without bioenergy and complementary measures (*NoBio* scenario), and water withdrawals do not exceed environmental flow requirements. At the same time, food prices are not affected (same level as in *NoBio*). Hence, the combination of environmental protection and land-sparing measures investigated here avoids additional sustainability trade-offs under large-scale bioenergy deployment.

Figure 3 Environmental and socio-economic indicators for 2050 at the global scale: CO2 emissions from land-use change (top left), nitrogen losses due to fertilizer use (top right), water withdrawals exceeding environmental flow requirements (bottom left), and food price index (bottom right). Solid black circles mark indicator levels without bioenergy production (*NoBio* scenario). For scenarios with bioenergy production, values outside black circles indicate adverse side-effects of bioenergy production (e.g. CO2 emissions from land-use change in *Bio*). The environmental protection and land-sparing measures included our scenarios apply not only to bioenergy production but to agricultural production in general. Hence, co-benefits can occur, which are indicated by scenario results located inside black circles (e.g. nitrogen losses in *Bio-EffNfert*). Solid red circles mark indicator levels of bioenergy production without complementary measures (*Bio* scenario). If scenario results are located outside solid red circles for a particular indicator, the underlying measure increases adverse-side effects of agricultural production in this dimension, i.e. the measure, which may successfully lower other impacts, involves a new sustainability trade-off (e.g. unsustainable water withdrawals and food price index in *Bio-REDD*). Own illustration by PIK.

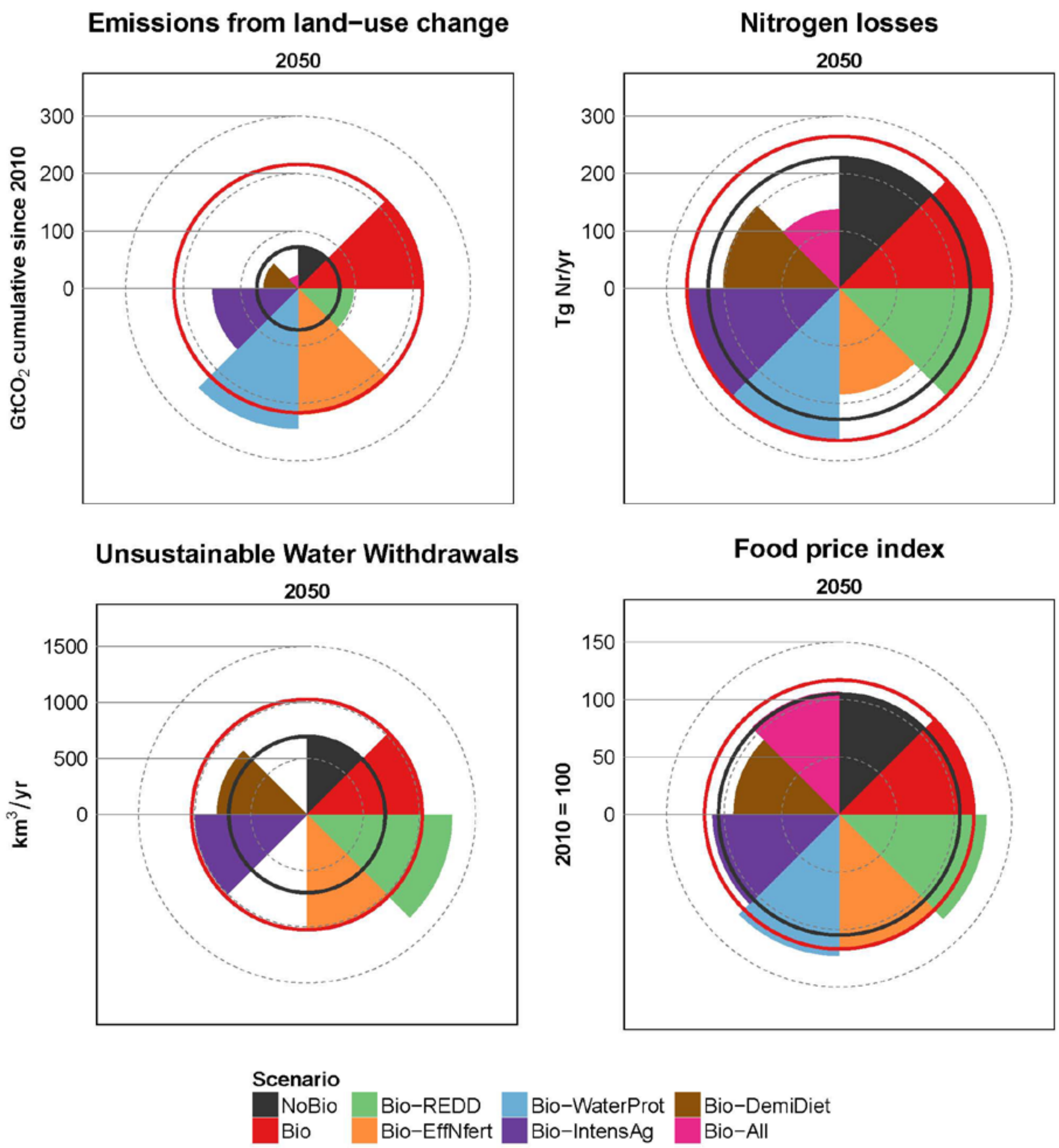


Table 2 Summary of study design. Demand for 2nd generation bioenergy (grasses and fast-growing trees) increases linearly from 0 EJ/yr in 2010 to 133 EJ/yr in 2050 and 300 EJ/yr in 2100.

Scenario	Bio-energy	Environmental protection and land-sparing measures
NoBio	off	-
Bio	on	-
Bio-REDD	on	Price on CO2 emissions from the conversion of forests and other carbon-rich ecosystems
Bio-EffNfert	on	Improved soil nitrogen uptake efficiency
Bio-WaterProt	on	Protection of water resources based on environmental flow requirements
Bio-IntensAg	on	Increased agricultural productivity and higher livestock productivity
Bio-DemiDiet	on	Limited consumption of animal products to half of current Western diets and lower household waste
Bio-All	On	Combination of REDD, EffNfert, Water-Prot, IntensAg and DemiDiet

4 Sustainable decarbonisation of power supply

Only a tight budget remains for future CO2 emissions to achieve the climate targets set in the Paris Agreement, i.e. to limit warming to well below 2 °C or even 1.5 °C. This chapter summarizes key insights from recent research partially funded by this project regarding opportunities of and requirements for power system decarbonisation in line with these climate targets.

In this chapter we explore the role of the electricity supply sector for deep emissions reductions consistent with these targets. Our research shows that the electricity supply sector - and especially renewable energy from wind and solar power – has great potential to play a pivotal role for deep decarbonisation, while also promoting environmental sustainability.

1) The early and deep decarbonisation of electricity supply is a pivotal element of effective climate protection strategies. Electricity generation offers the greatest potential for low cost emission reductions in the short term. Given the long lifetimes of power supply infrastructure, achieving these potentials at an early stage is essential to avoid further lock-in into a fossil-intensive system. Moreover, low-carbon electricity supply systems pave the way towards further emission reductions in the buildings, industry and transportation sectors via accelerated electrification.

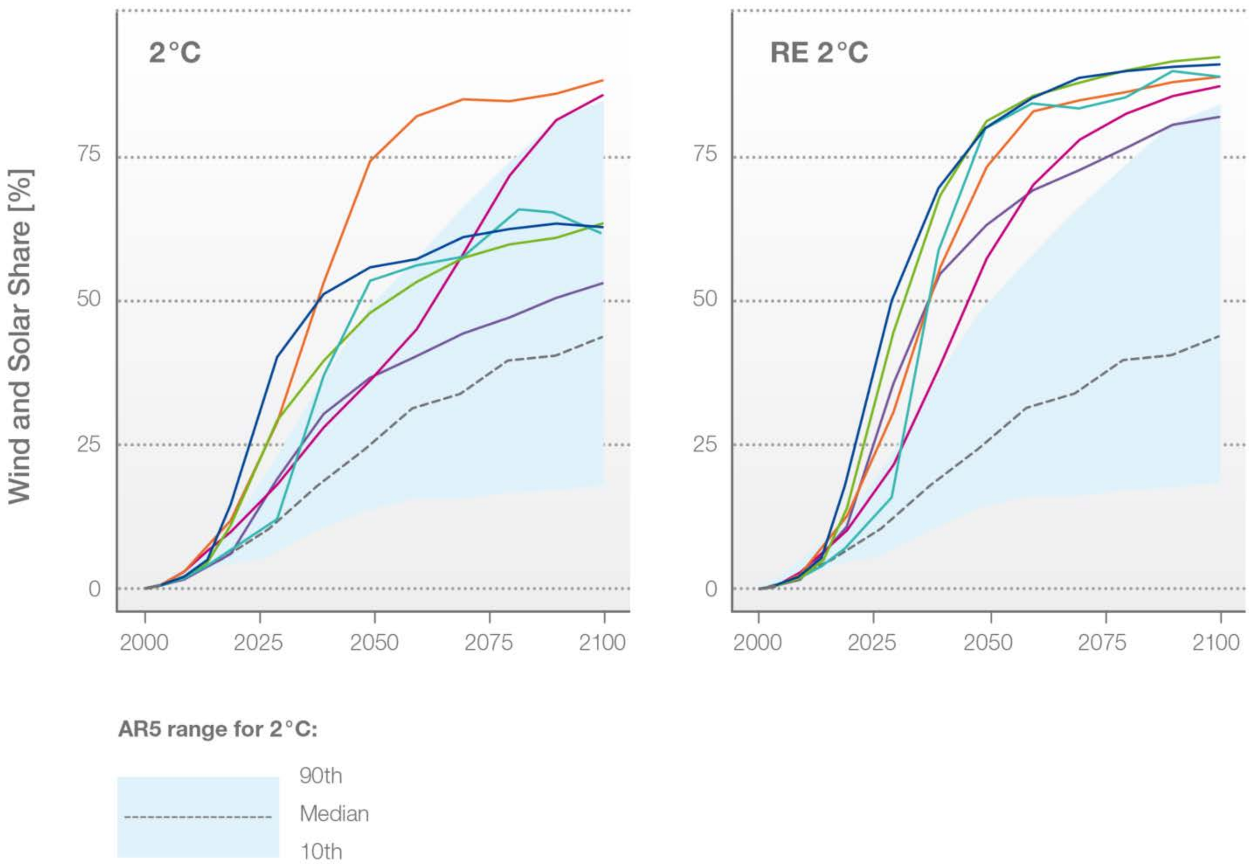
2) The energy supply sector can be almost fully decarbonised through renewables without the use of nuclear and carbon capture and storage (CCS). The power supply sector offers a particularly high degree of technology flexibility, with wind, solar, hydropower, nuclear, and CCS as alternative mitigation options. With average market growth rates of more than 40 % per year for solar PV, and around 20 % for wind power over the last decade, these "new renewable" energies are often seen as the most promising technologies for a low-carbon future. Moreover, wind and solar technologies have experienced substantial cost reductions in recent years due to technological progress and economies of scale, while nuclear and CCS expansion programs in many countries have failed to realize. As there is still plenty of potential for additional innovation, further cost decreases are expected in the future.

New insights on system integration of wind and solar power

Many scholars and decision-makers have argued that the prospects of wind and solar power are diminished by the variability and uncertainty of their supply; unlike conventional electricity from fossil or nuclear plants, their electricity output fluctuates with varying wind speed and solar radiation. Latest scenario-based research provides more robust insights into the potential role of variable renewable energy sources for carbon-free electricity supply and climate change mitigation. Most previous modelling studies have underestimated the role of wind and solar because of overly conservative assumptions on technology costs and the challenges related to coping with a variable renewable electricity supply. Recent analyses with improved modelling systems show that wind and solar power can be major contributors to power system decarbonisation, and that almost carbon-free electricity supply can be achieved based on renewables alone (Creutzig et al. 2017; Luderer et al. 2017; Pietzcker et al. 2016).

We find that power supply can be almost fully decarbonised without nuclear and CCS. Our scenarios feature shares of combined wind and solar of 60 - 80 % by mid-century. An expansion of grid interconnectors and the provision of additional flexibility, via increasing deployment of electricity storage or demand response, are important factors for enabling such renewable-based power systems, while limiting curtailment of wind and solar electricity to less than 15 % in most regions.

Figure 4 Share of wind and solar in global power supply until 2100 in climate protection scenarios consistent with the well-below 2°C limit with the full technology portfolio (left panel) and renewable focused decarbonisation without nuclear and CCS (right panel). Blue shaded areas indicate the 10 - 90 % range of results from 2 °C scenarios assessed in the IPCC's Fifth Assessment Report (AR5). The coloured lines represent results from different models participating in the EU project ADVANCE (2013-2016). This graph shows that power sector decarbonisation without nuclear and CCS is possible. Own illustration by PIK.



3) Power sector decarbonisation comes with environmental co-benefits, as it requires a dramatic decrease of fossil fuel combustion, which causes a wide range of environmental impacts. How-ever, climate policies can also have adverse side-effects, for example land requirements to produce biofuels. Integrated assessment models in combination with lifecycle assessment approaches allow quantifying alternative power sector decarbonisation strategies in terms of their environmental impacts. They show that co-benefits of the low-carbon transformation tend to outweigh adverse side effects. In particular, climate friendly power systems considerably reduce air pollution, and greatly decrease the release of toxicants to watersheds, e.g. from leaching coal mine dumps.

4) Wind- and solar-based power-sector decarbonisation strategies have considerably smaller non-climate environmental impacts than strategies based on nuclear and CCS as main technology options. A comparison of the risk profiles of renewables-based power sector decarbonisation (with nuclear and CCS excluded from the portfolio of technology options) to a climate protection strategy largely based on nuclear and CCS (with wind and solar limited to a combined share of 10 %) shows that renewables-based strategies are superior in terms of minimizing environmental impacts. They greatly decrease air and water pollution as well as total water demand and avoid ionising radiation impacts from the use of nuclear power. An important drawback of a renewables-based strategy is the substantial use of mineral resources, such as steel, copper and aluminium required for constructing wind turbines, solar panels, grid infrastructure and storage systems. While wind and solar emerge as being comparatively environmentally friendly, biomass is associated with greater environmental impacts than the other renewable supply options. Similarly, hydropower can result in substantial indirect greenhouse gas emissions and upstream energy requirements. Even though it contributes less than 10 % of power supply in either scenario, bioenergy dominates the land footprint of power supply, exceeding land requirements for wind and solar installation, and for grid infrastructure.

Figure 5 Comparison of non-climate environmental impacts of power sector decarbonisation strategies consistent with the well-below 2°C limit based on new renewables (high contribution of wind and solar) or conventional technologies (high contribution of CCS and nuclear). Impacts are shown for 2050 and relative to those that would occur in the absence of climate policies, i.e., values smaller than 1 indicate a decrease of impacts due to climate policies. Note that a logarithmic scale is applied. Own illustration by PIK.

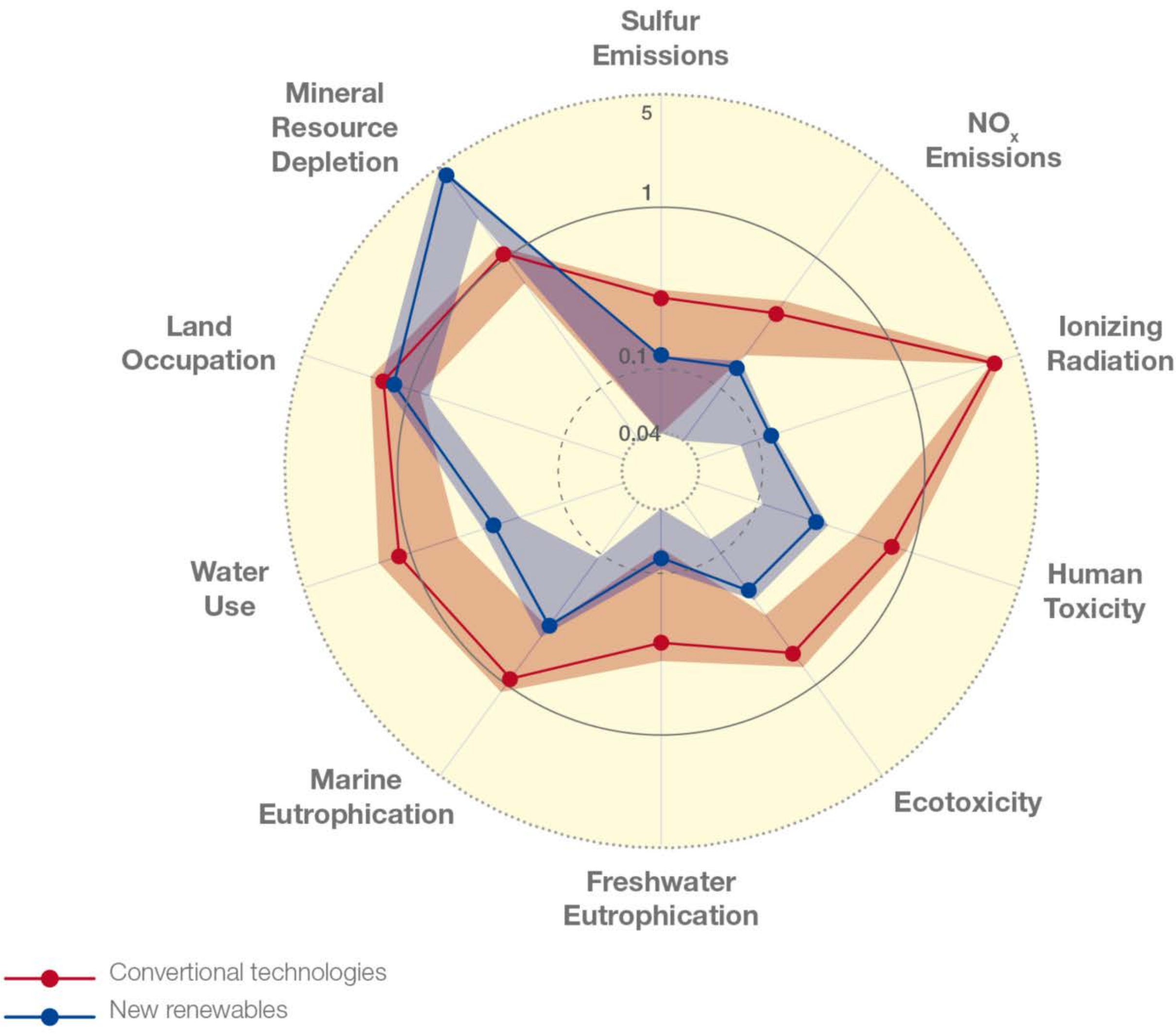
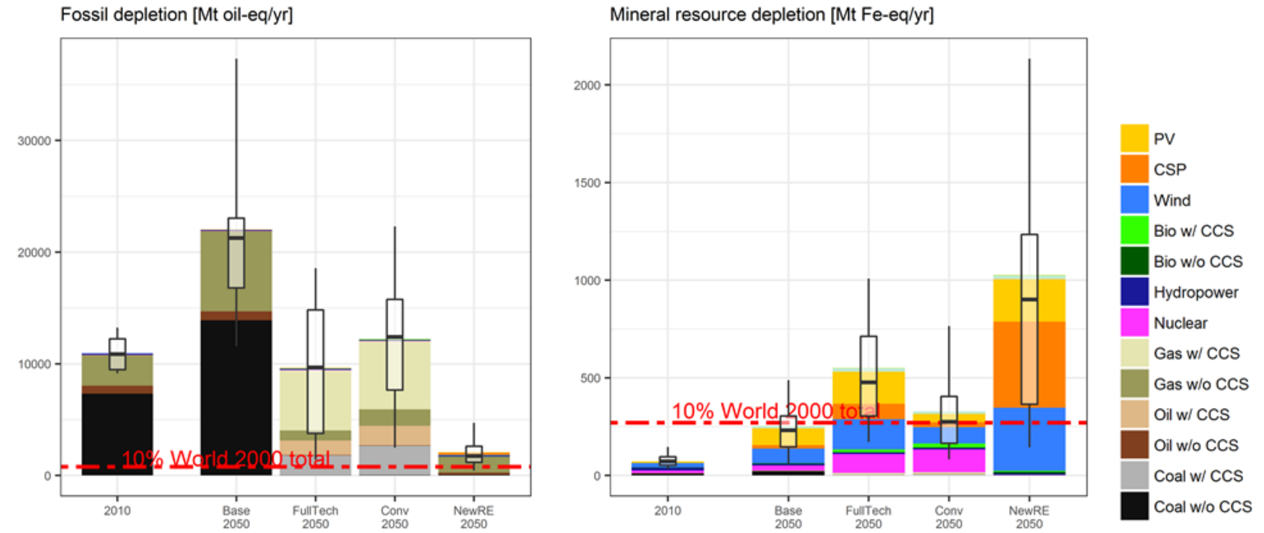


Figure 6 Comparison of fossil (left) and mineral resource requirements (right) of baseline (“base” - no climate policy) scenarios, as well as power sector decarbonisation strategies consistent with the well-below 2°C limit with full technology portfolio (“FullTech”), based on conventional technologies (“conv” - high contribution of CCS and nuclear), new renewables (“NewRE” - high contribution of wind and solar). Fossil resource depletion aggregates life-cycle coal, oil and gas requirements. Mineral resource depletion accounts for a basket of bulk metals, such as iron, copper and aluminium. Own illustration by PIK.



5 Sustainability oriented mitigation pathways towards 1.5 and 2°C

The fundamental transformation of the global energy and land-use systems required for limiting global warming to well below 2°C or even 1.5°C has strong implications for many other sustainability targets defined by the sustainable development goals (SDGs). A few previous meta-studies have analysed synergies and adverse side-effects of mitigation for further sustainability targets. Similarly the roles of individual technologies and policies have been analysed for specific aspects. However, there is to date no integrated and comprehensive analysis of energy and land-use policy approaches that simultaneously achieve climate change mitigation targets while also addressing other non-climate sustainability objectives. Here we fill this gap by analysing the impacts of different types of policies on various sustainability indicators in the context of long-term climate targets of 1.5 or well below 2°C, using the integrated energy-economy-landuse modelling system REMIND-MAgPIE. We find that a combination of different policy types, deviating from the least-cost paradigm thus far prevalent in mitigation research, seems most promising in reducing sustainability risks across all dimensions studied. Hence, mitigation policies need to be complemented by wider SD policies for realizing pathways that could be more socially accepted as they are most likely to achieve multiple societal objectives at the same time.

Background

Climate change and sustainable development have a long history in international diplomacy, but only recently have the two agendas merged into a common discourse. Climate change has been enshrined in the sustainable development goals, as goal 13; and the Paris Agreement is strongly framed in the context of sustainable development (United Nations General Assembly 2015; UNFCCC 2015).

At the heart of this common discourse is a growing appreciation that the success of both agendas directly depends on the success of the other. Arguably, sustainable development cannot be achieved unless the most severe, pervasive and potentially irreversible climate impacts of business-as-usual development to people and natural systems can be avoided – requiring limiting warming to well below 2°C or possibly even 1.5°C (Edenhofer et al. 2014; IPCC 2014a, b). However, the means by which such emissions reductions are achieved are highly consequential for future human development. For instance, a growing dependence on bioenergy and large-scale negative emissions deployments may not be conducive to long-term food security and biodiversity objectives (REF).

Conversely, it is becoming increasingly apparent that sustainable development is key to deep and persistent long-term emissions reductions. Avoiding a new generation of fossil fuel infrastructure – at both the supply and demand side – is fundamental to remaining within the 2°C target (Davis and Socolow 2014; Erickson and Tempest 2015; Creutzig et al. 2016). Decentralized and low-carbon energy systems offer energy services with social, health and economic benefits far beyond that of fossil counterparts (West et al. 2013; Alstone et al. 2015). And more broadly, a research agenda embracing politically engaged social change offers a wide scope for shifts in habits and consumption, raising the possibility that human well-being can progress and flourish in the absence of fossil fuels and energy intensive development pathways (Lamb and Steinberger).

Designing climate policies that address wider sustainable development considerations – and non-climate development policies that reinforce these mutual goals – is a challenge that has received little attention to date, or has been dispersed in its efforts. Yet, many studies have explored the linkages between climate change mitigation and individual sustainability objectives. A stream of work has focused on climate change mitigation and access to household energy services (Riahi et al. 2012; Pachauri et al. 2013; Cameron et al. 2016). Another series of studies have explored the economic implications of climate change mitigation, including policy costs in the short and long term, technological progress, carbon and energy price development, energy security aspects, and innovation and upscaling (Wilson et al. 2013; Jewell et al. 2014; Bertram et al. 2015; Rogelj et al. 2015). The wider impacts of climate change policies for other environmental problems such as air pollution (West et al. 2013; Strefler et al.

2014), water scarcity (Bonsch et al. 2014), deforestation and land-use change or biodiversity have also been studied quite intensively (van Vuuren et al. 2015), while social aspects have only been scarcely addressed.

Yet, there have been few attempts so far to study synergies and trade-offs across multiple sustainability objectives quantitatively. There is work to place existing literature and expertise on individual SDG dimensions into a broader framework of interactions and potential policy measures (Weitz et al. 2017). Van Vuuren et al. (2015) build a set of sustainability objectives into the IMAGE modelling framework, highlighting the importance of bioenergy policy as a locus for trade-offs between climate change mitigation, food security, and biodiversity. Von Stechow et al. (2016) (see Chapter 2) and Jakob and Steckel (2016) focus on the sustainability metrics that can be extracted from a compilation of pre-existing integrated assessment scenarios for meeting 2°C, finding that short-term mitigation ambition and rapid energy demand reduction softens trade-offs and improve SDG synergies. In a similar vein, Obersteiner et al. (2016) assess SDG trade-offs in the land system, highlighting again the important role of demand shifts, here in the form of reduced meat demand, for realizing multiple SDG objectives. Efforts from the sustainable development community are also driving forward an integrated understanding of the 'energy-water-food nexus', a framework that has attracted both integrated modelling studies and bottom-up case studies (Biggs et al. 2015; Keairns et al. 2016). Scenario literature assessing sustainability implications of the 1.5°C limit is unavailable. Yet, it is the class of scenarios where such evidence is most critical, because it involves the most aggressive mitigation efforts including those that remove carbon dioxide from the atmosphere at a very large-scale (Luderer et al. 2013; Rogelj et al. 2015; Rogelj, J. et al. 2017). Furthermore, so far there is little analysis that explicitly considers the impact of policy choices regarding mitigation and sustainability aspects.

In this chapter we provide an integrated analysis of sustainability impacts of 2°C, but also 1.5°C scenarios, across a comparatively large number of sustainability dimensions. We develop customized indicators from a coupled energy energy-land-use modelling system that capture key aspects of individual SDGs in a consistent framework. We analyse how policy packages addressing climate and non-climate objectives can help to manage wider sustainability impacts and identify relevant synergies and trade-offs.

This analysis builds on the work in Chapter 2, but goes beyond it in important aspects:

- It builds on new scenarios, designed to inform policy choice (while Chapter 2 uses existing scenarios that were not designed to directly represent different policy choices but rather technology availability)
- The design of policies not only looks at individual policies, but also considers the combination of different approaches.
- It not only considers well below 2°C scenarios, but also analyses more ambitious mitigation scenarios leading to 1.5°C warming above pre-industrial at the end of the 21st century.

Study outline

We employ the integrated energy-economy-climate model REMIND (Leimbach et al. 2010; Luderer et al. 2013) coupled to the Landuse-Management model MAgPIE (Lotze-Campen et al. 2008; Popp et al. 2014). Further details on the two models and their coupling can be found in the methods section below. We differentiate the policy scenarios analysed here along two dimensions:

"Policy paradigm": We analyse scenarios with either a default climate-only policy paradigm following cost-effective achievement of climate targets via carbon prices increasing exponentially at 5% p.a., or combined policy packages that deviate from the least-cost paradigm by adding dedicated sustainability regulations in the land-use and energy sector (water and forest protection measures, efficient management practices, nuclear phase-out, fossil fuel subsidy phase-out, electric vehicle mandates), increased early mitigation action (carbon prices starting higher but increasing at a lower rate of 3% p.a) and lifestyle changes towards less material, energy and land intensive-lifestyles.

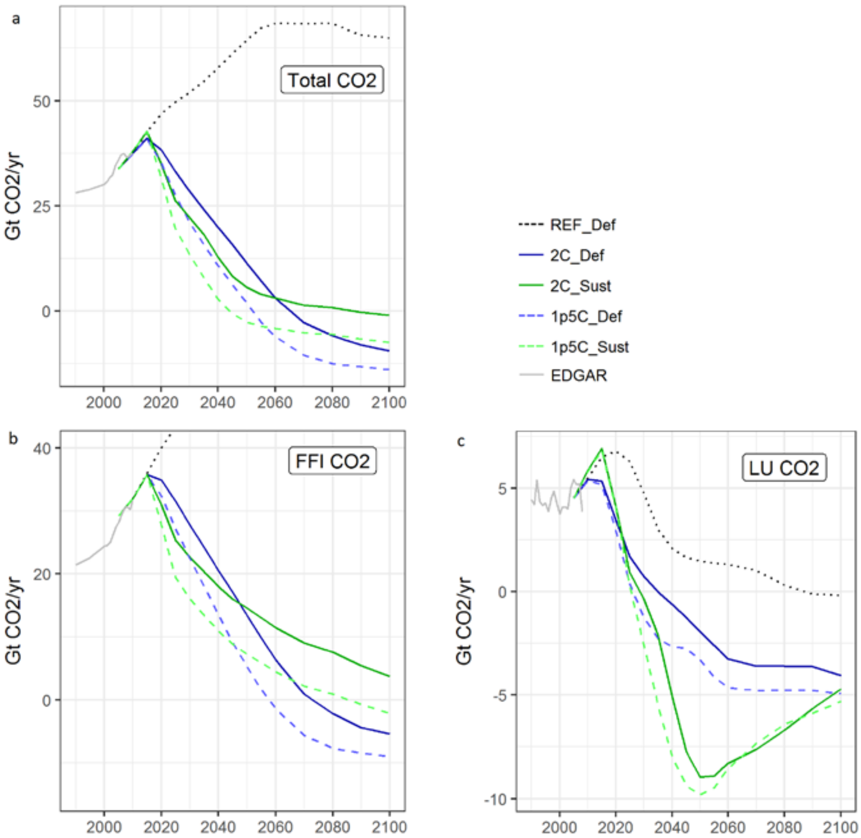
Stabilization target: We analyse both a 2°C scenario, defined as a bound on cumulative total CO2 emissions from 2011-2100 of 1000 Gt, and a 1.5°C scenario (400 Gt CO2 2011-2100).

Table 3 Overview of scenarios

Policy paradigm: / Stabilization target:	Default / climate-only	Regulation	Early action	lifestyle	Additional sustainability measures
Baseline (current policies or no climate policies)	REF_Def				
2°C target	2C_Def	2C_regul	2C_early	2C_life	2C_Sust
1.5°C target	1.5C_Def	1.5C_regul	1.5C_early	1.5C_life	1.5C_Sust

The scenarios with additional the additional policy package ("_Sust") are characterized by steeper emission reductions at the beginning and higher emissions in the second half of the century in comparison to the least-cost mitigation policy scenarios (Figure 1). Further diagnostic graphs for the scenarios, including land-use changes, primary energy mixes and electricity generation mixes can be found in the methods section below.

Figure 7 CO2 emissions in the five main scenarios. Panel a shows total CO2 emissions, and panels b and c the two separate components fossil fuel and industry (FFI) and Land-Use (LU). Historic data is from EDGAR (EDGAR 2011). Own illustration by PIK.



We analyze the scenarios along multiple indicators, to identify sustainability trade-offs and synergies associated with particular policy choices. Table 2 lists the indicators used and broadly links them to particular SDGs. While no indicator alone is able to fully capture any of the SDGs, 11 of the 17 SDGs are at least partially considered in this analysis.

The goal of our study is to evaluate the effectiveness of different policies in fostering sustainable development, because the wider sustainability implications of climate policy pathways are critical for their social acceptability. Doing so we identify crucial interdependences, both synergies and trade-offs, of the various dimensions, dependent both on chosen climate targets and policy frameworks. Importantly however, we do not try to monetarize all sustainability risks in order to minimize an aggregate overall risk indicator. We also do not try to define thresholds for intolerable risk levels in the various sustainability dimensions, given that this involves normative judgments and for many indicators is not possible in a meaningful way on the global level we consider.

Further explanations on the modelling tools, the scenario design and the choice and definition of indicators can be found in the Methods section below. (For more complete information, see the resulting peer reviewed publication in Annex 5 & 6.)

Table 4 Analysed indicators and relevant SDGs

Indicator	Relevant SDG
Food price index in 2030	SDG 1 (No poverty) SDG 2 (zero hunger)
Water withdrawal for irrigation and energy in 2030	SDG 6 (Clean water and sanitation) , SDG 15 (Life on land)
Short-term costs (cumulative consumption losses from 2015-2050, expressed in % of cumulative baseline consumption, with 3% discounting). Please note that these costs do not take into account avoided damages due to lower warming.	SDG 1 (No poverty) and SDG 8 (Decent work and economic growth)
Long-term costs (cumulative consumption losses from 2050-2100, expressed in % of cumulative baseline consumption, with 3% discounting). Please note that these costs do not take into account avoided damages due to lower warming.	SDG 1 (No poverty) and SDG 8 (Decent work and economic growth))
SO2 emissions from power generation in 2030	SDG 3 (Good health and well-being) SDG 11(sustainable cities and communities)
Temperature increase in 2050 relative to 2015	SDG 13 (Climate Change)
Cumulative uranium extraction 2015-2100	SDG 12 (Responsible consumption and production)
Cumulative sequestered CO2 2015-2100	SDG 12 (Responsible consumption and production)

Results

1. Benefits and risks of 2°C mitigations pathways

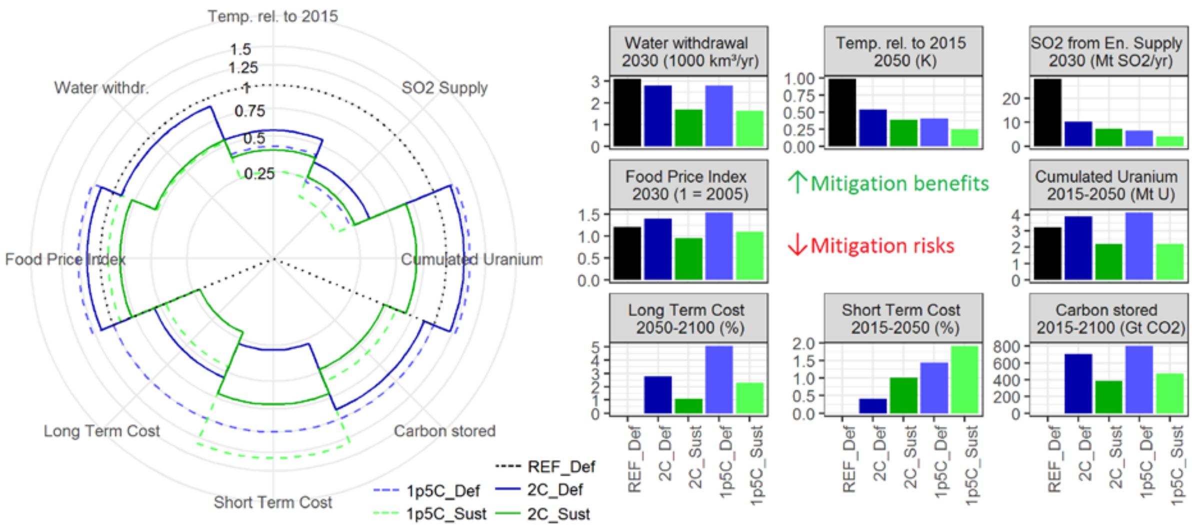
In agreement with previous literature (Jakob and Steckel 2016; Stechow et al. 2016) (see also Chapter 2), our comparison of sustainability indicators for default mitigation-only policy scenarios towards 2°C

(2C_Def) identifies both a range of benefits of mitigation, but also various sustainability risks associated with mitigation (Figure 2).

The most important benefits of mitigation here identified include the reduction of temperature increase until 2050 by more than 0.5 °C compared to business as-usual (REF_Def), and reduced air pollution from fossil fuel use. Furthermore, near-term water withdrawal is slightly reduced due to lower deployment of thermal power generation technologies.

In terms of mitigation risks, we look at two controversial technologies, nuclear and CCS, as well as three different socio-economic indicators. For nuclear, a substantial amount of uranium is used already without climate policies, but mitigation via carbon pricing leads to a further increase in deployment of this low-carbon power technology. In contrast, CCS is not used at all without climate policies, so the risk only appears through mitigation policies. The dominant majority of this sequestration is employed in combination with biomass to achieve carbon dioxide removal, offsetting gross emissions from those energy applications that continue to rely on fossil fuels (freight transport, aviation and shipping, as well as certain industrial processes). In the default 2°C scenario, the loss of cumulative consumption in the first 35 years of mitigation is less than 0.5% of baseline consumption, while losses in the second halve of the century amount to close to 3%.

Figure 8 Sustainability indicators for 2C and 1.5 scenarios with mitigation-only policy (Def) and combined sustainability policy package (Sust). Panel a shows values for the upper 5 indicators normalized to the No-policy baseline reference, and the other 3 indicators normalized to the 1.5_Def scenarios. Panel b shows absolute values. Own illustration by PIK.



2. 1.5°C has slightly higher co-benefits but clearly increased risks

An evaluation of the default policy 1.5 °C scenario ("1p5_Def") along the 8 indicators shows that both benefits and risks increase further relative to the default 2°C scenario. In the mid-century warming indicator, there is only incremental improvement possible (0.13°), as the inertia of both capital stocks and the climate system has already locked-in a certain amount of warming until mid-century.

In the three risk indicators related to food prices, CCS and nuclear, risks also increase incrementally compared to the 2°C scenario. In addition, the risk values for costs show a much more substantial increase, with a doubling of the long-term costs and even a tripling of short-term costs. However, these results do not take into account the avoided damages of increasing ambition to 1.5°C, which, among other benefits, is likely to be decisive for the future of coral reefs and the livelihoods that depend on them (Schleussner et al. 2016).

3. Sustainability regulation and increased early action exhibit clear trade-offs

The first policy package ("_regul") consists of directly regulating a range of controversial technologies and management practices in both the energy and land-use systems, as well as incentivizing some of the more sustainable alternatives. The yellow line and bars in Figure 3 show how this package of policies impacts the overall sustainability assessment under 2°C policies.

Three of the indicators, water withdrawal, uranium and CCS deployment directly show the desired effect of the regulation. In the temperature and SO2 indicators, this policy package also shows a slight benefit, which is mainly due to the reduced reliance on CCS, which in turn leads to somewhat higher carbon prices and thus slightly faster decarbonisation. In the socio-economic indicators, however, clear trade-offs emerge. While the adverse effect on food prices and long-term costs is very small, short term costs increase by more than 50% due to the regulation.

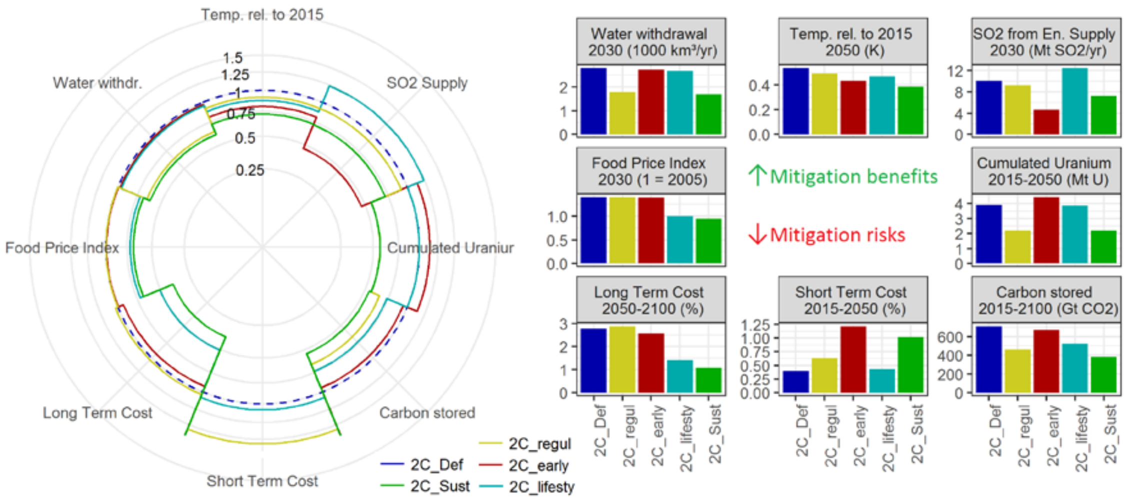
In addition to the illustrated trade-off between socio-economic and other sustainability risks, each individual component of regulation can also lead to further trade-offs that are masked here by showing the result for a policy package combining various regulatory policies at once. For example, a reduction of nuclear power through the moratorium on new plants would on its own also lead to higher SO2 emissions and higher requirements for CCS, as some of the generation would have to be replaced by fossil power (partly with CCS).

The second policy package ("_early"), increased early action, shifts the mitigation burden in time, by introducing a higher initial carbon price increasing exponentially at a rate of 3% p.a., compared to the 5%p.a. increase in the default policy scenarios. Additionally, faster retirement of existing capacity is allowed, and the carbon price applied in the land-use system is halved, which leads to less afforestation.

The primary impact of this policy package is a faster phase-out of fossil fuels in many sectors, which is mirrored in lower 2050 temperatures and the SO2 indicator which is more than halved in comparison to the default 2°C scenario. The higher initial carbon prices have opposites effect for nuclear and CCS: Nuclear use is expanded faster in the near-term to make up for the faster phase-out of fossil fuels. CCS on the other hand cannot be scaled-up as fast in the medium-term, given that it is so far not in operation at a relevant scale. Furthermore, the overall demand for negative emissions is slightly reduced, as faster near-term mitigation results in less cumulative emissions that need to be compensated by carbon dioxide removal.

The main trade-off resulting from early action policy package, as with the regulation, is the much increased short-term cost stemming from higher initial carbon prices.

Figure 9 Sustainability indicators for five different 2°C scenarios, differentiated by policy mix. Panel a shows all values normalized to the 2C_Ref scenario, panel b shows absolute values. Please note that the relative values for Short term cost for the 2C_early and 2C_Sust scenarios are very large and thus outside the range shown in panel a, but the absolute values can be seen in panel b. Own illustration by PIK.



4. Lifestyle changes lead to improvements in economic indicators, but limited impacts in others

The third policy package consists of a promotion of less material- and energy-intensive lifestyles and healthier diets relying on fewer animal products. Such a policy reduces pressures both in the energy and land-use system, which are mutually linked via bioenergy. This leads to considerable reductions in long-term costs and food security risks. Through lower demand for fuels, midcentury temperatures and CCS requirements for negative emissions are also reduced. In contrast to the other two policy types, no stark trade-offs can be observed, but some indicators are hardly impacted at all, such as water withdrawal or uranium use. The 25% increase in SO2 emissions stems from the slightly lower carbon prices, which leads to a slightly slower phase-out of coal power generation, the main source of SO2 emissions in the supply sector.

5. Combined policies have complementary impact, lead to overall lowest risk levels along most dimensions

The previous sections have shown that individually, each of the three considered policy approaches is effective in reducing risks in some dimensions, but none manages to bring down risks across the full set of indicators considered. Furthermore, the regulation and early action package exhibit substantial trade-offs, with especially the short-term cost indicator increasing considerably. Therefore, a combination of all three policy packages ("Sust") might be considered as a means to complement individual policies and soften their risks. Indeed, this results in the lowest risk levels in 6 out of the 8 indicators considered in Figures 2 and 3. This not only applies to the 2°C scenarios, but equally is valid for the 1.5°C scenarios shown in Figure 2.

The two indicators where the combined sustainability policies do not lead to the lowest values are SO2 emissions and short-term costs. In terms of SO2 emissions, the sustainability combination is slightly less effective than the early action package alone, as the counteracting effect of the lifestyle package leads to somewhat lower carbon prices and therefore a less rapid coal phase-out. The sustainability package however still exhibits a 25% lower risk value than the default 2°C scenario. Short-term costs is thus the only indicator, in which the combined sustainability policies lead to a higher risk value than the default 2°C scenario with carbon pricing alone, only slightly lower than the maximum value in this indicator as exhibited by the 2C_early scenario.

Limitations

To put our results into perspective, it is crucial to first recapture the limitations of the study. Importantly, the present study, as any explorative analysis of potential future pathways, has to operate under the framing condition of deep uncertainties, both with respect to future development of some crucial input parameters of the analysis (socio-economics, technology availability, costs and performance, etc.), as well as the structural relationship within and between the analysed systems (investments and demand for energy services, demand for agricultural products, working fundamentals of both energy and other markets, etc.). Our way of generating useful insights under these circumstances is to concentrate on the qualitative effects of analyzed policy interventions, and exploring underlying system effects.

Further limitations are necessarily implied by the chosen scope of the study. We opted for performing the analysis on the global level, which has the advantage of capturing various relevant feedbacks that stem from the global markets existing for various commodities nowadays. Furthermore, temperature change as one of the central indicators in our analysis can only be deducted from a global analysis. We furthermore decided to also implement the policies in a globally homogeneous way. This simplifying assumption has the advantage that the interactions of the different policy types can be nicely worked out. These choices however mean that our analysis does not speak to some crucial elements of global sustainability like within- and across-country equity issues.

Policy implications and outlook

The results have highlighted the importance of synergies and trade-offs that exist between climate and non-climate sustainability dimensions. Given the inherent requirement for value judgments when it comes to weighing the different dimensions against each other, our results reinforce the call for an as broad as possible public deliberation on the exact mix of policies to take within each country (Jakob and Steckel 2016).

The results highlight that the default policy scenario, in which mitigation is achieved by the single instrument of carbon pricing, exhibits much higher risk values in a range of sustainability indicators in comparison to other scenarios that include further sustainability measures. The standard argument for implementing climate policies via pricing only is cost-effectiveness. Accordingly the core trade-off in scenarios where sustainability risks are reduced by additional policies is higher near-term mitigation costs. To what extent avoided monetary damages associated with the sustainability risks would compensate for the higher mitigation costs is an important but challenging avenue for future research. This could be explored from a utilitarian (monetary) perspective, or from a robust account of human needs that ensures transparency in normative claims and aligns well with the sustainable developments goals (Gough 2015).

The relative impact of additional sustainability impacts is very similar in 1.5°C scenarios and 2°C scenarios. When comparing the 2°C scenarios with the respective 1.5°C scenarios, the latter lead to lower sustainability risk values, while the costs are higher. This highlights how the choice of near-term policy pathways to take not only depends on evaluation of short-term sustainability risks, but has to consider the compatibility to long-term climate targets.

The analysis of different types of sustainability policies identifies their relative strengths and weaknesses. Dedicated regulation on specific risks fares best in reducing each risk individually, but typically increase pressures in other parts of the system. An increase of early action in comparison to cost-optimal policies brings down a range of risks and leads to lower mitigation costs in the long run, but results in considerably increased near-term costs. Arguments related to inter-generational equity and hedging against higher climate sensitivity values or less effective long-term mitigation might still call for such approaches. As in chapter 2, lifestyle changes towards healthier diets and less energy- and material-intensive consumption patterns reduce a range of sustainability risks and appear to be the most promising option considered here, but it is unclear to what extent policy-makers have a direct handle to bring about the assumed lifestyle changes. . Certainly this would require confronting prevailing social habits, as well as the constellation of private interests that sustain, reproduce and benefit from existing consumption patterns (Fuchs et al. 2016) . Yet questions of power are also fundamental to the adequate translation of "regulation" and "early action" scenarios into policies directed at the fossil fuel and energy system sectors. Thus combination of all three policy approaches, adjusted for local circumstances and preferences emerges as the most promising way for balancing climate and other sustainability risks.

Methods

Models

The scenarios in this study have been constructed with the coupled REMIND-MAgPIE integrated assessment modelling framework. This has been first presented in Kriegler et al. 2016, from which the following description is adapted.

The REMIND-MAgPIE integrated assessment modelling framework consists of an energy-economy-climate model (REMIND) (Bauer et al., 2008, 2012; Leimbach et al., 2010a,b; Luderer et al., 2013, 2015) coupled to a land-use model (MAgPIE) (Lotze-Campen et al., 2008; Popp et al., 2010, 2014b). REMIND (Regional Model of Investment and Development) is an energy-economy general equilibrium model linking a macro-economic growth model with a bottom-up engineering based energy system model. It covers eleven world regions, differentiates various energy carriers and technologies and represents the dynamics of economic growth and international trade (Leimbach et al., 2010a,b; Mouratiadou et al., 2016). A Ramsey-type growth model with perfect foresight serves as a macro-economic core projecting growth, savings and investments, factor incomes, energy and material demand. The energy system representation differentiates between a variety of fossil, biogenic, nuclear and renewable energy resources (Bauer et al., 2012, 2016a,b; Klein et al., 2014a; Pietzcker et al., 2014a,b). The model accounts for crucial drivers of energy system inertia and path dependencies by representing full capacity vintage structure, technological learning of emergent new technologies, as well as investment mark-ups for rapidly expanding technologies. The emissions of greenhouse gases (GHGs) and air pollutants are largely represented by source and linked to activities in the energy-economic system (Strefler et al., 2014a,b). Several energy sector policies are represented explicitly (Bertram et al., 2015), including energy-sector fuel taxes and consumer subsidies (Schwanitz et al., 2014). The model also represents trade in energy resources (Bauer et al., 2015). A detailed model description can be found at http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_REMIND

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a global multi-regional economic land-use optimization model designed for scenario analysis up to the year 2100. It is a partial equilibrium model of the agricultural sector that is solved in recursive dynamic mode. The objective function of MAgPIE is the fulfilment of agricultural demand for ten world regions at minimum global costs under consideration of biophysical and socio-economic constraints. Major cost types in MAgPIE are factor requirement costs (capital, labour, and fertilizer), land conversion costs, transportation costs to the closest market, investment costs for yield-increasing technological change (TC) and costs for GHG emissions in mitigation scenarios. Biophysical inputs (0.5° resolution) for MAgPIE, such as agricultural yields, carbon densities and water availability, are derived from a dynamic global vegetation, hydrology and crop growth model, the Lund-Potsdam-Jena model for managed Land (LPJmL) (Bondeau et al., 2007; Müller and Robertson, 2014). Agricultural demand includes demand for food (Bodirsky et al., 2015), feed (Weindl et al., 2015), bioenergy (Popp et al., 2011), material and seed. For meeting the demand, MAgPIE endogenously decides, based on cost-effectiveness, about intensification of agricultural production (TC), cropland expansion and production relocation (intra-regionally and inter-regionally through international trade) (Dietrich et al., 2014; Lotze-Campen et al., 2010; Schmitz et al., 2012). MAgPIE derives cell specific landuse patterns, rates of future agricultural yield increases

(Dietrich et al., 2014), food commodity and bioenergy prices as well as GHG emissions from agricultural production (Bodirsky et al., 2012; Popp et al., 2010) and land-use change (Humpenöder et al., 2014; Popp et al., 2014b).

Emissions in the land-use and energy sectors are interlinked by overarching climate policy objectives and the deployment of bioenergy (Klein et al., 2014b; Popp et al., 2014a; Rose et al., 2014). REMIND and MAgPIE models are coupled to establish an equilibrium of bioenergy and emissions markets in an iterative procedure (Bauer et al., 2014). The atmospheric chemistry- climate model MAGICC (Meinshausen et al., 2011) is used to evaluate the climate outcomes of the REMIND-MAgPIE emission pathways.

Scenario definitions

In this study, we construct various transformation pathways that lead to the same long-term climate target, but are differentiated by five different policy paradigms. The scenarios assume a middle-of-the road socio-economic development as in the SSP2 scenario (Fricko et al. 2017).

For the long-term climate target, we investigate both a "well below 2°C" scenario and a "1.5°C by 2100" scenario. As in Luderer et al. (in review), the climate targets are defined via a bound on cumulative total CO2 emissions (including emissions from fossil fuel combustion, industrial processes and land-use and land-use change). Adherence to the bound is implemented via an iteratively adjusted emissions price on CO2, N2O and CH4, using 100 year global warming potentials. Emission pricing starts in 2020 and prices increase exponentially until 2060 with 5% in the default policy setting and linearly thereafter. For the well-below 2°C target, cumulative 2011-2100 emissions are limited to 1000 Gt CO2, whereas the 1.5°C scenario has a budget of 400 GtCO2. These budget values represent a likelihood of 66% of staying below 2°C throughout the 21st century in the "well below 2°C" scenarios, as well as 66% of staying below 1.5°C after 2100 in the 1.5°C scenario (Clarke et al. 2014; Rogelj et al. 2015).

The sustainability oriented 2°C and 1.5°C scenarios assume additional policy interventions on top of the carbon price. Since these additional policies influence the portfolio of mitigation options, they typically also change the carbon price level required to achieve the same climate target. The additional policy interventions are either implemented by adding bounds to the solution space (for example requiring a certain share of new vehicle sales to be electric vehicles), by assuming a different value for a certain input parameter (food and baseline energy demand for example are input parameters to the model), or by adjusting the distribution of mitigation effort over time (early action scenario).

Indicators

At the core of the analysis is the multi-dimensional comparison of the different long-term targets and policy paradigms along a set of sustainability indicators presented in Table 2. In the following, the details of the indicators, including their calculation is presented.

Food price index

As an indicator of changes in food commodity prices, we analyse a chained Laspeyres price index that weights prices based on food baskets in the previous period. Food baskets are defined on exogenous regional demand. We show the values in the year 2030, with the 2005 index level set to 1.

Water withdrawal for irrigation and energy

This indicator is a summation of water withdrawal for irrigation of both crop and energy plantations, as well as for cooling purposes in power generation. We show the values in the year 2030.

Table 5 Overview of settings in the different policy paradigms scenarios.

	Setting in default scenarios	Policy setting	Policy setting active in scenario….			
			regulation	Early action	lifestyle	Sustainability
Trade in agricultural products	Agricultural trade barriers decline by 0.5% per year	Agricultural trade barriers decline by 1% per year	X			X
1st generation biofuels (Lotze-Campen et al. 2010)	Constant at 2020 levels	Phase-out	X			X
Water protection (Bonsch et al. 2015)	No dedicated measure	Protection of water resources based on environmental flow requirements resulting in around 40% lower agricultural water withdrawals in 2050 globally	X			X
Forest protection (Popp et al. 2017)	Linear increase of protected forest areas by factor 1.5 between 2010 and 2100	Linear increase of protected forest areas by factor 4 between 2010 and 2100	X			X
Nitrogen efficiency (Bodirsky et al. 2014)	Soil nitrogen uptake efficiency converges to 60% globally by 2050; constant thereafter	Soil nitrogen uptake efficiency converges to 75% globally by 2050, and rises to 85% by 2100	X			X
Agri. waste management systems (Bodirsky et al. 2014)	30% adoption rate for anaerobic digesters by 2050.	60% adoption rate for anaerobic digesters by 2050.	X			X
Feeding convergence (Popp et al. 2017)	Faster increase of productivity in low income countries; continuing increase in high income countries.	20% more efficient	X			X
Nuclear power (Bauer et al. 2012)	No constraint	No new plants after 2020	X			X
CCS injection	1% of total capacity per year	0.5% of total capacity per year	X			
Electric vehicles (IEA 2016)	No dedicated support	Dedicated support, mandating 8,5 and 2% LDV market share in different regions in 2020, each rising by 2% points per year	X			X

	Setting in default scenarios	Policy setting	Policy setting active in scenario….			
		afterwards (capped at 80% around 2060)				
Carbon pricing	Exponential increase at 5% p.a. from 2020-2060, linear increase thereafter	Exponential increase at 3% p.a. from 2020-2060, linear increase thereafter		X		X
Pricing of land-use emissions		Halved in comparison to defaults case		X		X
Early retirement of coal power plants	Max 6% linearly per year (full phase-out earliest in 2035)	Max 10% linearly per year (full phase-out earliest in 2030)		X		X
Fossil fuel subsidies (Schwanitz et al. 2014; Bertram et al. 2015)	Phase-out until 2050	Phase-out until 2030		X		X
Final energy demand	SSP2 (~700 EJ in 2050, 900 EJ in 2100)	SSP1 per capita demand with SSP2 population assumptions: -25% at the end of the century (~600EJ in 2050, 700 in 2100)			X	X
Agricultural demand (Bodirsky et al. 2014; Stevanović et al. 2017)	Continuation of current trends, with doubling of total food demand by the end of the century, caused by the increase in population and income.	-20% below reference at the end of the century, 50% for livestock products			X	X

Short-term costs

In our scenarios, we do not represent losses from climate damages. Therefore, deviation through climate and sustainability policies from the no-policy baseline by design leads to lower consumption. The consumption difference between each policy scenario and the respective no-policy baseline (REF_Def and REF_Sust) is called consumption loss. The consumption in scenarios calibrated to different exogeneous demand trajectors ("Lifestyle" and "Sust") cannot be directly compared to the default baseline, therefore for these scenarios a separate baseline (REF_Sust) is used to determine the cost indicators.

As short-term cost, we then define the cumulative consumption loss from 2015-2050, discounted at 3%, and expressed relative to the cumulative consumption in the respective baseline over the same period, again with 3% discounting. Importantly, these costs do not take into account avoided damages due to lower warming.

Long-term costs

This indicator is calculated in the same way as short-term costs, only considering the period 2050-2100.

SO2 emissions from power generation

This indicator is chosen to represent the air pollution dimension of the scenarios. While other species and SO2 from other sources also have an important role for the total burden of air pollution, this variable was chosen as the different policies here lead to very different outcomes already in the short term. We show the values in the year 2030. This indicator is meant to complement the exogenously given long-term warming target.

Mid-term warming

The temperature trajectory resulting from the modeled emission trajectories in the different scenarios is calculated using the reduced-form climate model MAGICC (Model for Greenhouse gas Induced Climate Change) (Meinshausen et al. 2011). Adverse impacts from climate change and ocean acidification are not only determined by the long-term warming level, but also the medium-term warming induced by near to medium term emissions. This indicator is meant to complement the long-term warming target which is prescribed by the exogenously given carbon budgets. The mid-term warming indicator shows the increase in 2050 relative to 2015. Temperature increase relative to pre-industrial is ~1°C higher, as warming in 2015 is reported at ~ 1°C above pre-industrial.

Cumulative uranium extraction

To illustrate the range of risks associated with nuclear power use, from ionizing radiation related to uranium mining, to safety risks inherent to the operation of nuclear power plants, the security risk related to proliferation as well as long-term risks of nuclear waste disposal, we show cumulative uranium extraction from 2015-2100, interpolating years linearly between the 5-year (-2060) and 10-year time steps.

Cumulative sequestered CO2

To illustrate the risks associated with the geological sequestration of CO2 we show the cumulative sequestered carbon from 2015-2100, interpolating years linearly between the 5-year (-2060) and 10-year time steps.

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Annex 1

Stechow C von, Minx JC, Riahi K, Jewell J, McCollum DL, Callaghan MW, Bertram C, Luderer G, Baiocchi G (2016) 2 °C and SDGs: united they stand, divided they fall? Environ Res Lett 11:034022. doi: 10.1088/1748-9326/11/3/034022

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LETTER

2 °C and SDGs: united they stand, divided they fall?

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Abstract

The adoption of the Sustainable Development Goals (SDGs) and the new international climate treaty could put 2015 into the history books as a defining year for setting human development on a more sustainable pathway. The global climate policy and SDG agendas are highly interconnected: the way that the climate problem is addressed strongly affects the prospects of meeting numerous other SDGs and vice versa. Drawing on existing scenario results from a recent energy-economy-climate model inter-comparison project, this letter analyses these synergies and (risk) trade-offs of alternative 2 °C pathways across indicators relevant for energy-related SDGs and sustainable energy objectives. We find that limiting the availability of key mitigation technologies yields some co-benefits and decreases risks specific to these technologies but greatly increases many others. Fewer synergies and substantial trade-offs across SDGs are locked into the system for weak short-term climate policies that are broadly in line with current Intended Nationally Determined Contributions (INDCs), particularly when combined with constraints on technologies. Lowering energy demand growth is key to managing these trade-offs and creating synergies across multiple energy-related SD dimensions. We argue that SD considerations are central for choosing socially acceptable 2 °C pathways: the prospects of meeting other SDGs need not dwindle and can even be enhanced for some goals if appropriate climate policy choices are made. Progress on the climate policy and SDG agendas should therefore be tracked within a unified framework.

1. Introduction

There is hope that 2015 will be remembered as a defining year for setting human development on a more sustainable pathway. Two important milestones were reached. On 25 September, a new development agenda was adopted in New York aimed at eradicating poverty and facilitating inclusive development within ever tighter planetary boundaries. Economic, social and environmental progress will be tracked across a set of agreed sustainable development goals (SDGs). The SDG framework is intended to manage trade-offs and maximize synergies across the 17 different goals and associated 169 targets (Griggs *et al* 2013).

On 12 December, countries agreed upon a new international climate treaty, the Paris Agreement, at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP21) in Paris. It ‘aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by holding the increase in the global average temperature to well below 2 °C above pre-industrial levels’ (UNFCCC 2015a).

Both processes are highly interrelated: SD is an explicit part of the Paris Agreement, while avoiding dangerous climate change features as one of the SDGs (#13). In fact, failure in one process would undermine the success of the other. Stringent and sustained mitigation is a *necessary* condition for SD, because unabated climate change will exacerbate many of today's development issues and negate future improvements (see Fleurbaey *et al* 2014). However, it is an *insufficient* condition for SD, because some 2 °C pathways could, if not designed properly, undermine SD in non-climate dimensions. For example, pathways with a limited short-term ambition like the current INDCs may have higher SD risks than more ambitious ones. Such broader SD implications could delegitimize some 2 °C pathways or even the 2 °C target itself (Edenhofer and Kowarsch 2015). SD further hinges on the successful implementation of non-climate policies that complement or support climate policies in other dimensions. Thus, identifying socially acceptable 2 °C pathways requires framing climate policy in a broader SD context.

Assessments of alternative mitigation pathways so far have mainly focused on characterizing the underlying technological and economic challenges (Clarke *et al* 2014), but less is known about the wider social, economic and environmental implications. For example, many 2 °C pathways project large amounts of bioenergy demand in the second half of this century. It is highly debated in the literature whether these can be provided sustainably: food security, place-specific livelihoods, water availability and biodiversity are amongst the critical issues being discussed (Creutzig *et al* 2012, Smith *et al* 2014). At the same time, many 2 °C pathways project potential health gains and co-benefits for other sustainability objectives. The balance of these co-effects is poorly understood, particularly on the supply side, because risks of alternative 2 °C pathways for non-climate sustainability objectives have not yet been systematically analyzed (von Stechow *et al* 2015).

In this letter, we analyze the implications of alternative 2 °C pathways for SD risk dimensions by drawing on existing, publicly available inter-model comparison results from integrated energy-economy-climate models—henceforth referred to as integrated models (see SI section 1, available at stacks.iop.org/ERL/11/034022/mmedia). We demonstrate how broadening the analytical framework can allow both for a more informed public debate about alternative 2 °C pathways and how achieving the climate SDG may affect the prospects of meeting other energy-related SDGs. This is important both for critically discussing the relationship between the international climate policy and SDG agendas as well as for identifying stringent mitigation pathways that are socially acceptable.

2. Methods

Choosing appropriate climate policies is an exercise in risk management for which it is key to understand and evaluate relevant uncertainties (Kunreuther *et al* 2013). We focus on uncertainties related to different model structures and assumptions, i.e. 'model uncertainty' (Drouet *et al* 2015) and draw on results from a structured inter-comparison exercise of integrated energy-economy-climate models, AMPERE (Kriegler *et al* 2015, Riahi *et al* 2015). To complement existing literature, this data is used to assess relevant SD implications of alternative clusters of mitigation pathways that are consistent with the 2 °C target (see table S2) to initiate a public debate on their wider sustainability implications.

2.1. Choice of indicators for SD risks

The analysis builds on recent literature that explores a growing number of mitigation challenges with implications for non-climate sustainability objectives. Comprehensive discussions can be found in Clarke *et al* (2014, section 6.6) and von Stechow *et al* (2015, section 4). Table 1 summarizes the indicators that can be calculated from integrated model variables. Our choice of indicators is further constrained by the model structures, scenario runs, and reported variables as aggregated in the publicly available AMPERE database (https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB). For example, the coarse regional disaggregation of reported data in AMPERE impedes the analysis of indicators that are most relevant for inequality and poverty outcomes, such as energy supply per capita to satiate basic human needs (see Steckel *et al* 2013, Lamb and Rao 2015 and SI section 2 for a discussion of further model limitations). By systematically linking the chosen set of indicators to global SD risks, we can present a first, rough approximation of how alternative clusters of 2 °C pathways perform with respect to energy-related SDGs and other multilaterally agreed sustainable energy objectives (see table 2 and SI section 3 for a discussion on the indicator choice).

Due to the limited data availability, the analysis cannot address all relevant SDGs explicitly. But it enables us to provide an early contribution to public and scientific debates on the relationship between the international climate policy and SDG agendas and contribute to important early learning processes. To simplify the complex relationship between indicators, energy-related SDGs and other sustainable energy objectives (see figure S2), table 2 focuses on the strongest links between them. However, many indicators are also relevant for some cross-cutting SDGs, such as poverty and inequality, which are not addressed in the analysis (see SI section 3.1). The resulting set of indicators is relevant for judging both co-benefits of mitigation (air quality, oil security) and mitigation risks (upscaling of

Table 1. Integrated model literature on mitigation challenges with implications for non-climate sustainability objectives, with a focus on indicators that can be calculated from model variables. The different categories largely follow table 4.1 in Fleurbaey *et al* (2014). Due to strengths and weaknesses of the models, some mitigation challenges were only analyzed by individual models while others were covered by multiple models—mostly in the context of model inter-comparison projects. A comprehensive review on co-benefits and risks of mitigation is provided in von Stechow *et al* (2015).

Mitigation challenges	Indicators used	Selected literature
Economic/affordability challenges		
Aggregate economic costs of mitigation	Aggregated and discounted GDP/consumption losses	Kriegler *et al* 2013, Paltsev and Capros 2013, Clarke *et al* 2014, Kriegler *et al* 2014, Rogelj *et al* 2015
Transitional economic costs of mitigation	Consumption growth reduction	Kriegler *et al* 2013, Luderer *et al* 2013a, 2013b, Bertram *et al* 2015b
Carbon price growth	Carbon price jump over a decade	Rogelj *et al* 2013a, 2015
	Global energy price index	Luderer *et al* 2013b, Bertram *et al* 2015b
Energy price growth	Electricity price growth rate	Kriegler *et al* 2013, Rogelj *et al* 2015
Stranded fossil investment	Idle power plant capacity per year	Luderer *et al* 2013a, Rogelj *et al* 2013a, Bertram *et al* 2015a, Johnson *et al* 2015
Energy dependence	Trade flows between regions	Cherp *et al* 2013, Jewell *et al* 2013, 2014, Riahi *et al* 2012
Resilience of energy systems	Diversity of energy carriers in individual sectors (SWDI, HHI)	Cherp *et al* 2013, Jewell *et al* 2013, 2014
Depletion of oil reserves	Cumulative oil extraction	Sathaye *et al* 2011, Jewell *et al* 2013
Technological/innovation challenges		
Integration challenges of low-carbon technologies	Technological upscaling (rates)	Wilson *et al* 2013, Kim *et al* 2014, Eom *et al* 2015, Riahi *et al* 2015, van Sluisveld *et al* 2015, Bertram *et al* 2015a
Carbon intensity improvement	Carbon intensity reduction rates	Luderer *et al* 2013a, Edenhofer *et al* 2014a, Kriegler *et al* 2014, Riahi *et al* 2015
Social/institutional challenges		
Food price increase	World and regional market prices	von Braun *et al* 2008, PBL 2012, Lotze-Campen *et al* 2014, Wise *et al* 2014, van Vuuren *et al* 2015
Energy supply per capita/energy access	Final energy supply per year/access to modern fuels	van Ruijven *et al* 2012, Daioglou *et al* 2012, Krey *et al* 2012, Steckel *et al* 2013, Riahi *et al* 2012, Pachauri *et al* 2013, Lamb and Rao 2015, van Vuuren *et al* 2015
Nuclear proliferation	Enrichment/reprocessing facilities	Lehtveer and Hedenus 2015
Carbon market value	Value of cumulative emissions	Luderer *et al* 2013b, Bertram *et al* 2015b
Environmental challenges		
Resource extraction/use	Cumulative coal/uranium extraction	Rogner *et al* 2012, Bauer *et al* 2013, McCollum *et al* 2014
Bioenergy expansion	Biomass supply for energy	Creutzig *et al* 2012, Smith *et al* 2014
Air pollutant concentration	SO_2, BC, OC and NO_x emissions/concentrations	Riahi *et al* 2012, McCollum *et al* 2013a, Rogelj *et al* 2014, Rose *et al* 2014, Strefler *et al* 2014, van Vuuren *et al* 2015
Environmental risks of CO_2 capture and storage	CO_2 (fossil/biomass) captured and stored underground	Kriegler *et al* 2013, Eom *et al* 2015, Rogelj *et al* 2015, Smith *et al* 2016
Land use change	Global area changes for cropland, pasture, biomass, unmanaged land	Wise *et al* 2009, Reilly *et al* 2012, Lotze-Campen *et al* 2014, Popp *et al* 2014, Calvin *et al* 2014
Water shortage	Water use (mainly for bioenergy supply)	De Fraiture *et al* 2008, Arnell *et al* 2011, PBL 2012, Hejazi *et al* 2013, Bonsch *et al* 2016
Biodiversity loss	Mean species abundance (MSA)	PBL 2012, van Vuuren *et al* 2015
Peak atmospheric CO_2 concentration	Cumulative CO_2 emissions until mid-century	Joos *et al* 2011, Zickfeld *et al* 2012
Exceedance likelihood/overshoot risk	Likelihood of exceeding specific temperature/concentration target	Kriegler *et al* 2013, Luderer *et al* 2013b, Rogelj *et al* 2013a, 2013b

bioenergy and low-carbon electricity technologies) and has been shown to have substantial sustainability implications in many integrated models (Jewell *et al* 2013, McCollum *et al* 2013a, von Stechow *et al* 2015). It also includes an indicator for ocean acidification (Joos *et al* 2011, Zickfeld *et al* 2012) as well as three indicators that relate to transitional socioeconomic mitigation risks (growth in mitigation costs and energy prices as well as early retirement of coal capacity).

Our analysis presents SD risk profiles for alternative clusters of 2 °C pathways (see figures 2–4). The figures plot percentage changes over baseline projections in each dimension rather than comparing different metrics to each other and/or identifying critical thresholds because of the difficulty of incommensurability across different SD dimensions (von Stechow *et al* 2015). Care needs to be taken in the interpretation, because the different risks analyzed cannot be

Table 2. The link between relevant and available indicators calculated from integrated model variables, SD risk dimensions, and SDGs and other sustainable energy objectives. See figure S2 and SI section 3 for more details.

Indicators calculated from integrated model variables	SD risk dimensions affected by mitigation	SDGs and other sustainable energy objectives
Biomass supply for energy per year	Bioenergy expansion	Food security (SDG 2)
Cumulative BC and SO_2 emissions	Air pollutant concentration	Health via air quality (SDG 3.9)
Maximum decadal energy price growth	Energy price growth	Energy access (SDG 7)
Maximum decadal growth reduction	Consumption growth reduction	Economic growth (SDG 8.1)
Idle coal capacity per year	Stranded fossil investment	Full employment (SDG 8.3)
Maximum decadal PV and Wind upscaling	Wind & PV grid integration	Resilient infrastructure (SDG 9)
Cumulative global oil trade, cumulative oil extraction, fuel diversity of transport sector	Oil insecurity, transport sector reliance on oil	Ensure energy security[a]
Nuclear capacity expansion in Newcomers[b]	Nuclear proliferation	Peaceful use of nuclear power
Cumulative CO_2 emissions until mid-century	Peak atmospheric CO_2 concentration	Minimize ocean acidification (SDG 14.3)
CO_2 captured and stored per year	Environmental risks of CCS	Sustainable production (SDG 12.4)

[a] Due to the focus on global risks, the analysis is limited to oil security—the fuel with the highest scarcity concerns and high import dependence in most countries, lacking substitutes in transport (see SI section 3.1.7).

[b] We designed a new indicator that can draw on existing model variables (see SI section 3.2).

directly compared to each other, i.e. a larger increase in one risk is not necessarily more important than a smaller increase in another risk. Any interpretation of these risk profiles and any trade-off across risk dimensions requires evaluation and weighting—and this depends on the locally specific policy contexts and differ depending on individual priorities and risk perceptions (Slovic 1987, Jakob and Edenhofer 2014, Kunreuther *et al* 2014). The provided risk profiles therefore allow readers to make their own judgement about the relevance of changes in risk levels across SD dimensions. In this sense our analysis provides a starting point for a more informed public debate about the interaction between the mitigation and other energy-related SDGs that will put the normative aspects of such evaluation centre stage (see Edenhofer *et al* 2014b).

2.2. Choice of scenario data

Using model inter-comparison results from AMPERE allows us to take advantage of an internally consistent set of scenario specifications and harmonized input assumptions (Kriegler *et al* 2015, Riahi *et al* 2015). AMPERE work package 2 was chosen because (i) the data is publicly available, (ii) it consistently defines alternative short-term climate policy pathways across models until 2030, which is particularly relevant from an SDG perspective with a focus on short/medium-term developments, and (iii) it is the only model inter-comparison project that combines different types of constraints with respect to the stringency of short-term climate policies and the availability of mitigation technologies or energy demand growth assumptions (see table 3 and SI section S4). This is a key requirement for comprehensively exploring the SD risk dimensions of alternative 2 °C pathways. Yet the reported data does not shed light on all relevant dimensions. One shortcoming is the simplifying assumption of regionally homogeneous carbon prices without consideration of burden sharing regimes. This impedes an analysis of regional mitigation cost distributions (see den Elzen *et al* 2008, Luderer *et al* 2012, Tavoni *et al* 2013, Aboumahboub *et al* 2014, Tavoni *et al* 2015) and related SD implications.

The analysis draws on more than 20 scenario specifications from seven models: DNE21+, GCAM, IMAGE, MESSAGE, POLES, REMIND, and WITCH (for further information, see Riahi *et al* (2015) and SI section 4). To avoid comparisons of scenario results from different sets of models, most figures only draw on a subset of models as (i) not all models ran or found a solution for all mitigation scenario specifications, and (ii) not all models report results for all indicators due to model type, assumptions on parameters and constraints, or respective system boundaries (see table S1). The results are presented similarly to the scenario ranges in the Working Group III contribution to the IPCC Fifth Assessment Report (WGIII AR5) because this shows variability across models. However, given that the sample size is small and no systematic variation of all relevant model input assumptions was performed this variability does not represent full model uncertainty.

3. Results

The analysis is divided into two parts: we assess co-benefits of alternative 2 °C pathways before turning to their mitigation risk profiles. In each part, we systematically analyze different clusters of 2 °C pathways to understand the implications for SD outcomes of variations in (i) short-term climate policy stringency, (ii) availability of mitigation technologies or (iii) a combination of the two. Analyzing these clusters is highly relevant, because the current and projected INDC emission trajectories are not consistent with

Table 3. Naming of AMPERE mitigation scenarios (see table S3 and Riahi *et al* 2015 for details).

Model constraints	Description	Scenario name
Short-term targets (2030)		
Optimal policy	Emissions follow optimal 2 °C pathway	'OPT'
Low short-term target	High-ambition pathway (low short-term target): 53 Gt CO_2eq	'LST'
High short-term target	Low-ambition pathway (high short-term target): 61 Gt CO_2eq	'HST'
Technology cases		
Full portfolio of technologies	Full portfolio of mitigation technologies	'Full-Tech'
Low energy intensity[a]	Energy intensity improvements rate doubles	'LowEI'
Limited biomass	Limited global potential for bioenergy (<100 EJ/yr)	'LimBio'
No CCS available	CO_2 capture and storage never becomes available	'NoCCS'
Limited solar/wind potential	Limited potential (<20% of regional electricity supply)	'LimSW'
No new nuclear plants	No new nuclear capacity is added; older plants are retired	'NucOff'

[a] LowEI scenarios assume lower final energy demand due to improvements in energy efficiency and behavioral changes so that equivalent levels of overall energy service are supplied with lower final energy. Due to the limited representation of end-use technologies in some models, many models represent this in a stylized way.

optimal 2 °C pathways (UNFCCC 2015b) and the standard assumption of full technological flexibility is inhibited as significant upscaling of low-carbon technologies faces many different hurdles in practice[8]. Our analysis here focuses on the first half of the 21st century in which the interaction of short-term climate policies and the long-term climate target is strongest (Kriegler *et al* 2013, Luderer *et al* 2013a, 2013b, Riahi *et al* 2015, Eom *et al* 2015, Bertram *et al* 2015a).

3.1. Synergies across mitigation and sustainable energy objectives

Figure 1 uses cumulative indicators for (i) CO_2 emissions (Zickfeld *et al* 2012), (ii) the co-emitted air pollutants black carbon (BC) and sulphur dioxide (SO_2) and (iii) global oil extraction and trade as well as transport sector reliance on oil to present reduced SD risks, i.e. co-benefits of mitigation scenarios compared to baseline developments. Figure 1 shows that co-benefits in terms of lower ocean acidification, health and oil security increase relative to optimal 2 °C pathways by limiting the availability of key mitigation technologies, though considerable differences exist for different technologies and different sustainable energy objectives. This is for three main reasons:

(i) The unavailability of low-carbon technologies limits long-term mitigation potential, resulting in greater near-term emissions reduction requirements to meet a particular long-term climate goal. This leads to a decrease in fossil fuel use in the medium term (with lower cumulative global oil trade, oil extraction as well as transport sector reliance on oil) and the associated CO_2 emissions and co-emitted air pollutants. Limiting technologies that play a smaller role in reaching the long-term goal results in less dramatic transition requirements and fewer additional co-benefits.

(ii) When relying less on bioenergy and/or CO_2 capture and storage (CCS) technologies, the models are forced to switch more rapidly from fossil fuels to solar, wind and nuclear energy, which have higher co-benefits for air quality and oil security (Bruckner *et al* 2014, Hertwich *et al* 2015).

(iii) Limiting the deployment of bioenergy or CCS technologies that are associated with co-emitted air pollutants themselves (see SI section 3.1.9) additionally reduces air pollutant emission levels —which is not the case for limiting the availability of non-combustible RE or new nuclear capacity.

Admittedly, these results only cover a small subset of potential co-benefits from mitigation. However, the literature suggests that this finding may apply more broadly (see von Stechow *et al* 2015 for a review and synthesis): climate policy that leads to less fossil fuel use and energy demand growth in the near term drives a broad range of co-benefits beyond air quality and oil security, such as reduced water use and pollution, reduced ecosystem impacts, reduced health impacts (also due to more physical activity under changed mobility patterns and less fuel poverty in insulated housing) as well as more local employment opportunities.

[8] For example, CCS technology demonstration lags behind early IEA technology roadmaps (IEA 2009); nuclear power plant investments face high public acceptance challenges and even renewable energy (RE) investments are often opposed (Bruckner *et al* 2014). Unforeseen events or accidents (e.g., Fukushima) change risk perceptions of technologies (Rogers 1997, Patt and Weber 2014) making the analysis of limited mitigation technology portfolios interesting and relevant. To avoid unavailability of specific technologies, complementary technology policies (Somanathan *et al* 2014) could reduce additional costs (Kalkuhl *et al* 2013, Bertram *et al* 2015b) and ensure innovation activity, such as for CCS (von Stechow *et al* 2011) or PV (Peters *et al* 2012).

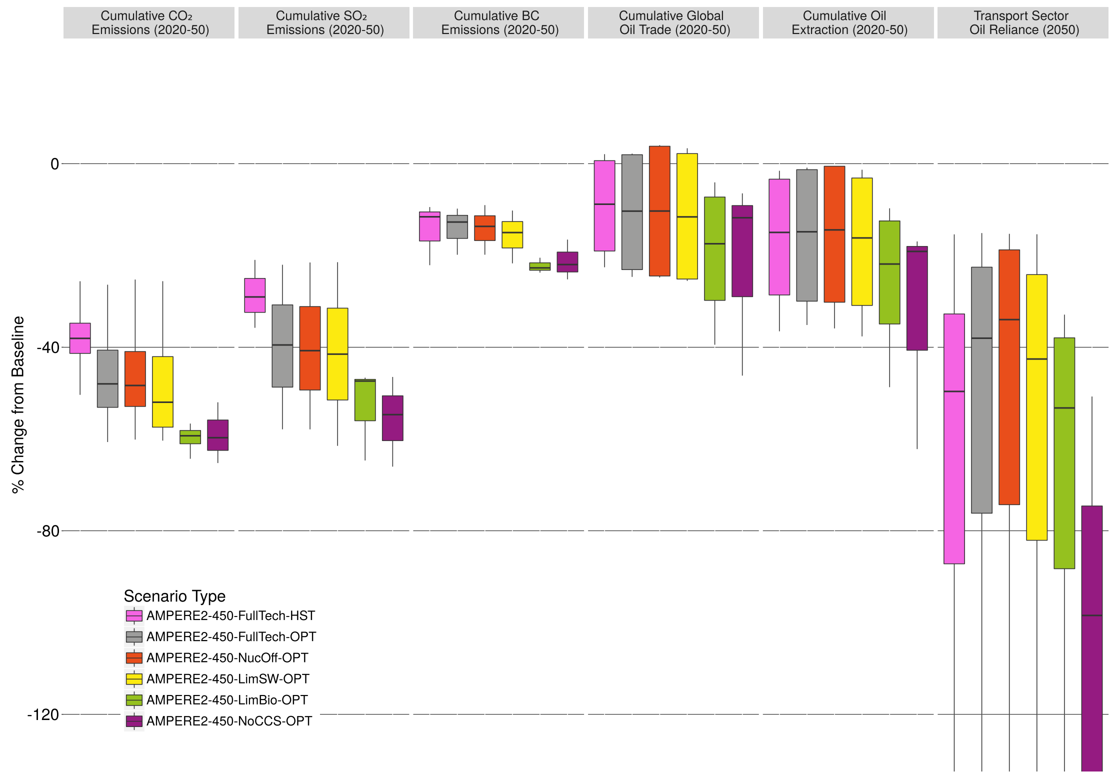

Figure 1. Percentage changes in indicators for co-benefits for reduced ocean acidification, air quality, oil security, and transport sector fuel diversity in alternative 2 °C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with delayed mitigation scenarios (pink) and immediate mitigation scenarios assuming no new nuclear capacity (red), limited potential for solar and wind energy (yellow) limited global bioenergy potential (green) or unavailability of CCS (purple). The thick black lines show the median of results, the coloured ranges show the interquartile ranges and whiskers show the minimum and maximum results.

Comparing optimal 2 °C pathways with scenarios assuming weak short-term climate policies confirms the positive effect of stringent mitigation in the near term on the magnitude of co-benefits (see figure S5 for the year 2030): weak short-term climate policies imply a reduction in co-benefits relative to those that could materialize in optimal 2 °C pathways. This effect is, however, not as obvious for cumulative 2050 values (see figure 1) because some of the additional mitigation efforts in the period 2030–2050 partially compensate for weak climate policies until 2030. Since the transport sector is characterized by faster capital turnover rates (at least with regard to the vehicle fleet) (Bertram *et al* 2015a), it can react more quickly to carbon price changes, compensating for higher emissions from sectors that are less flexible. This may lead, for example, to a higher fuel diversity in the transport sector in the year 2050 in delayed mitigation scenarios compared to optimal 2 °C pathways albeit at high uncertainty.

3.2. Trade-offs between mitigation and sustainable energy objectives

While constraining a particular mitigation technology may minimize the mitigation risks specific to that technology, it usually implies an increase in the deployment of other low-carbon technologies, which may incur other mitigation risks. Figure 2 shows that limiting the availability of specific technologies in 2 °C pathways with immediate global climate policies substantially increases the risk of not meeting other sustainable energy objectives. While the unavailability of CCS and limitation of bioenergy potential lead to the largest co-benefits (see figure 1), they also entail significantly higher SD risks. This can be explained by the promise of greater flexibility in near-term emission pathways that are still able to meet the long-term climate goal through the presence of carbon dioxide removal technologies, such as bioenergy with CCS (BECCS). Constraining BECCS deployment by limiting the global bioenergy potential or ruling out CCS deployment results in substantially higher deployment of other mitigation technologies in the medium term. The increase is much less pronounced for limiting the potential for solar and wind energy or assuming no new nuclear capacity (see figure S6).

Due to the different nature of the mitigation risks, it is unclear how decreasing risks in one dimension (e.g. bioenergy expansion or environmental risks associated with CCS deployment), can be traded off with risk increases in others (e.g. transitional growth reduction, energy price growth, nuclear proliferation or the technological challenges of integrating high amounts of fluctuating RE into existing power grids in a very

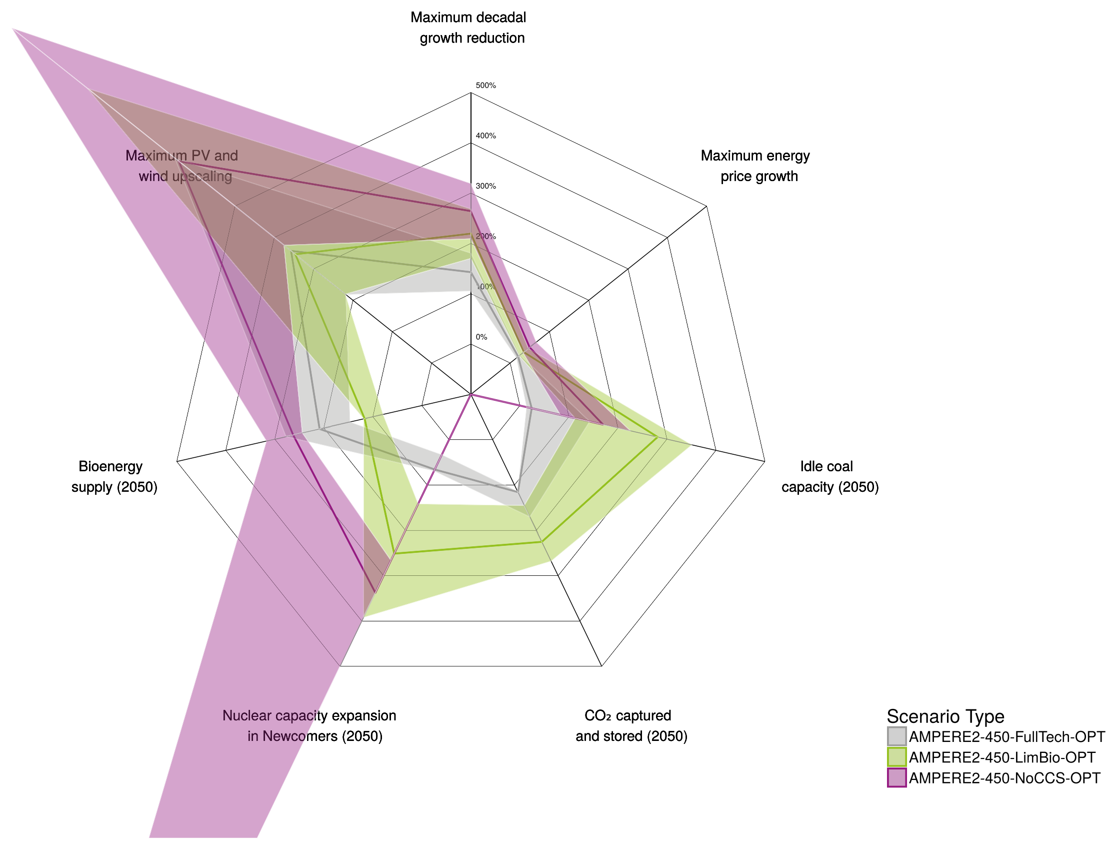

Figure 2. Percentage changes in mitigation risk dimensions in alternative 2 °C pathways for three integrated models (GCAM, MESSAGE, REMIND) relative to baseline scenarios and a CCS reference value, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey), with scenarios assuming limited global bioenergy potential (green) and unavailability of CCS (purple). Thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance to the 0%-line nor the total area covered by the shaded areas are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions (see discussion in section 2.2).

short time frame). For example, a 20%–30% increase in energy prices may have a much more immediate, adverse effect on the poor in many countries than a 4-7-fold increase in maximum decadal upscaling of variable renewable energy sources, which is primarily a technological and institutional challenge for infrastructure provision. Rather than aggregating effects across different risk dimensions, the purpose of this analysis is to make the trade-offs across alternative clusters of mitigation pathways transparent. Hence, the way the climate SDG is met can substantially alter the risks of not meeting other SDGs and sustainable energy objectives.

This is confirmed by figure 3: delaying stringent mitigation in the near term leads to a significant increase in mitigation risk levels in the medium term compared to optimal 2 °C pathways. With more GHG emissions before 2030, subsequent reductions are more expensive (Luderer *et al* 2013b) and need to be faster to stay below 2 °C (Eom *et al* 2015)—with implications for the grid integration of fluctuating RE (see SI section 3.1.6) and for stranded investments in coal capacity (Johnson *et al* 2015) and the associated job losses (Rozenberg *et al* 2014). The carbon lock-in effect hence manifests itself particularly in technological and economic risk dimensions. To a lesser degree, these effects can also be seen for delayed mitigation scenarios with more optimistic assumptions about short-term climate policies (see figure S7). Hence, delaying stringent mitigation implies forgoing potential paths with lower risks along multiple SD dimensions.

In contrast, assuming lower energy demand growth entails mitigation risk reductions relative to optimal 2 °C pathways (see figure 3). As each unit of energy not produced is free of pervasive supply-side risks, reducing energy demand by promoting energy efficiency in end-use sectors (e.g., consumer appliances), lifestyle changes (e.g., people living in higher-density areas and eating less dairy and meat) and structural changes in the economy (e.g., shifting to more service-oriented economies) is an important strategy both for mitigation and other sustainable energy objectives (von Stechow *et al* 2015).

Note that these reductions in energy demand growth are assumed to happen in the baseline scenarios, i.e. independent of the mitigation efforts and hence without a cost mark-up; it is unclear how future energy demand levels would develop under real-world conditions where clean energy and energy efficiency

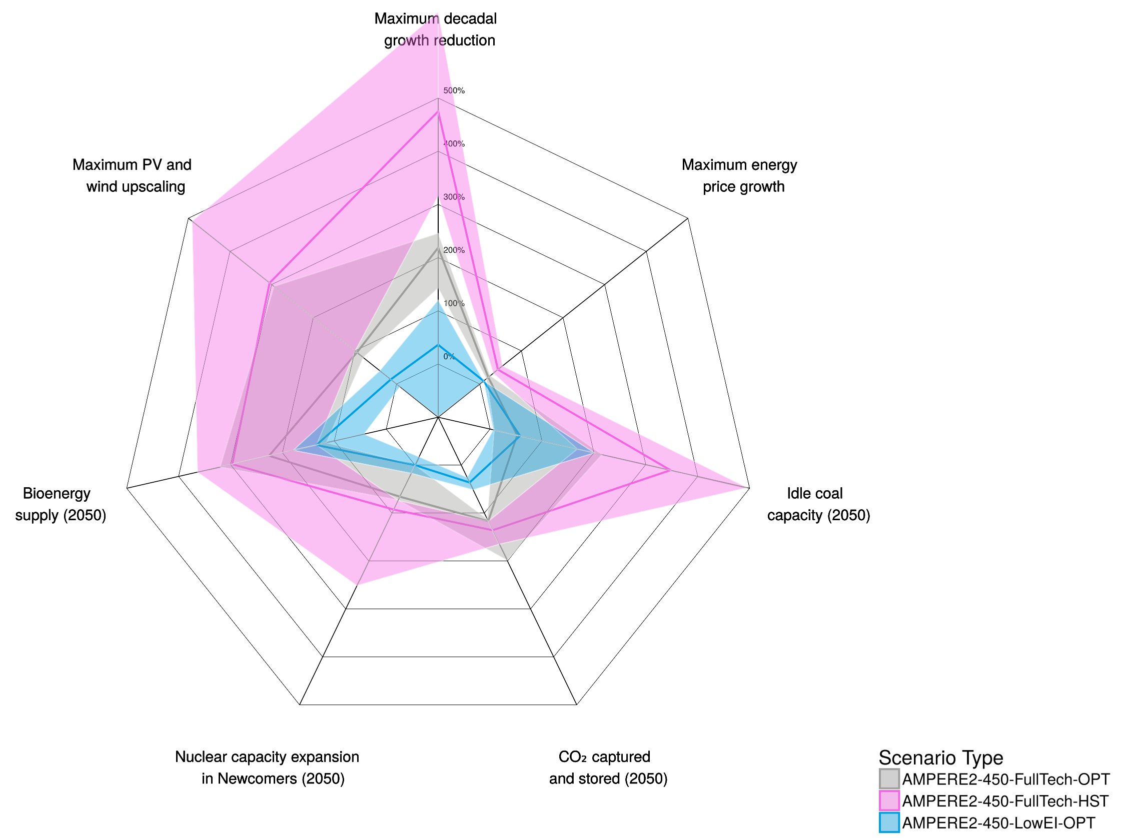

Figure 3. Percentage changes in mitigation risk dimensions in alternative 2 °C pathways for six integrated models (DNE21+, GCAM, MESSAGE, POLES, REMIND, WITCH) relative to baseline scenarios and a CCS reference value, comparing immediate (grey) with delayed mitigation scenarios (pink) and immediate mitigation scenarios with lower energy demand growth (blue). Neither the distance to the 0%-line nor the total area covered by the shaded areas are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions (see discussion in section 2.2).

projects may compete for limited funds (McCollum *et al* 2013b). Furthermore, the models do not simply prescribe lower energy supply at the expense of energy service supply, but alter assumptions on the average energy intensity improvement rates and, e.g., on the viability of more compact, public transit-friendly urban areas (Riahi *et al* 2015). This does not imply, however, that all integrated models project final energy supplies in mitigation scenarios that are consistent with minimum thresholds of energy consumption to satiate basic needs related to cooking, heating, health and other infrastructure (Steckel *et al* 2013, Lamb and Rao 2015). Hence, projections of energy demand from individual models need to be interpreted with care (see discussion in SI section 2).

3.3. Trade-offs between mitigation and sustainable energy objectives for combined model constraints

As current GHG emission trends keep tracking along business-as-usual (Edenhofer *et al* 2014a) and societal concerns grow with regard to upscaling of many low-carbon technologies (see footnote 8), 2 °C pathways with multiple constraints seem to mirror most closely developments observed in the real world. In fact, delaying stringent mitigation in combination with technological constraints risks no longer meeting the climate goal (Riahi *et al* 2015), substantially increases mitigation risks (see figure 4) and increasingly jeopardizes our ability to manage risk trade-offs. For CCS and bioenergy whose unavailability/limitations already show substantial risk trade-offs in immediate mitigation scenarios, most models can no longer find a solution (for CCS unavailability only DNE21+ and GCAM; for limited global bioenergy potential only GCAM, POLES, and REMIND) implying a high risk of not meeting the 2 °C target.

Figure 4 draws on AMPERE scenarios with multiple constraints but shows results for more optimistic —albeit not optimal — short-term climate policies[9], with and without limited global bioenergy potential. As models work close to their feasibility frontier, the additional constraint results in large mitigation risk increases. Even for non-biomass RE and nuclear energy, whose limitation/phase-out has rather small effects in immediate 2 °C pathways, risk trade-offs

[9] Figure 4 shows 'LST' scenarios (i.e. with more optimistic assumptions about near-term climate policies relative to 'HST' scenarios but still less stringent than optimal, see table 1) because only three models (GCAM, POLES, and REMIND) were able to find a solution for the 'HST-LimBio' scenarios.

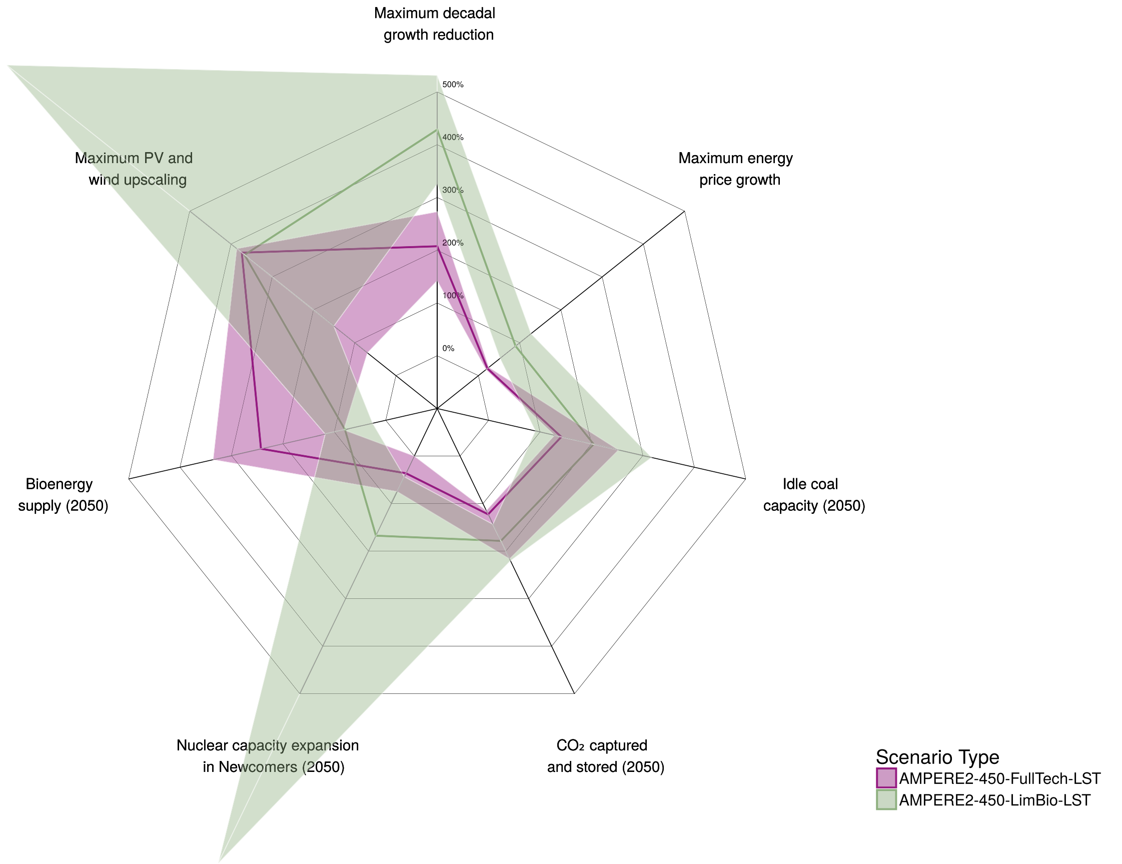

Figure 4. Percentage changes in mitigation risk dimensions in alternative 2 °C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to baseline scenarios and a CCS reference value, comparing delayed mitigation scenarios assuming full availability of mitigation technologies and weak short-term climate policies (purple) with delayed mitigation scenarios assuming limited global availability of bioenergy (green). Neither the distance to the 0%-line nor the total area covered by the shaded areas are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions (see discussion in section 2.2).

increase strongly for delayed mitigation scenarios in some dimensions (see figures S7 and S8).

4. Discussion

This letter presents a first attempt to shed light on the question of how alternative 2 °C pathways perform in non-climate SD dimensions and to draw conclusions about important interactions between stringent mitigation and other sustainable energy objectives. Figure 5 shows an overview of the different clusters of constrained 2 °C pathways relative to (each model's) optimal pathways (i.e., those with immediate mitigation, full technology portfolios, and conventional energy demand growth). We use 'optimal' scenarios as benchmarks because they show comparatively balanced risk profiles relative to baseline developments (see figures 2–4) and because they are commonly used as reference point for policy analysis, e.g. in the WGIII AR5 (Edenhofer *et al* 2014a). This enables the comparison of the various SD implications of one cluster of 2 °C pathways to those of all others and therefore facilitates an informed public debate on socially acceptable SD risks and thus the interaction between the international climate policy and the broader SDG agendas.

Note that 'optimal' pathways are not necessarily the most socially desirable because they may already involve unacceptable risks. Scientific analysis alone cannot judge whether a particular 2 °C pathway poses acceptable or unacceptable risks to society (Edenhofer and Minx 2014). Science can, however, explore alternative mitigation pathways and inform an enlightened public debate across SD risk dimensions in an iterative learning process (Edenhofer and Kowarsch 2015). For example, annual bioenergy supply is projected to reach up to 168 EJ (median: 158 EJ) in 2050 in optimal scenarios. These levels of biomass extraction may already be associated with fundamental challenges with respect to food security, place-specific livelihoods, water availability and biodiversity (Creutzig *et al* 2012, Smith *et al* 2014). These numbers further increase substantially over the second half of the century, reaching up to 862 EJ (median: 268 EJ) with growing requirements for removing CO_2 from the atmosphere via bioenergy with CCS (BECCS) technologies in many available scenarios (Clarke *et al* 2014). Many 'optimal' 2 °C pathways have therefore been

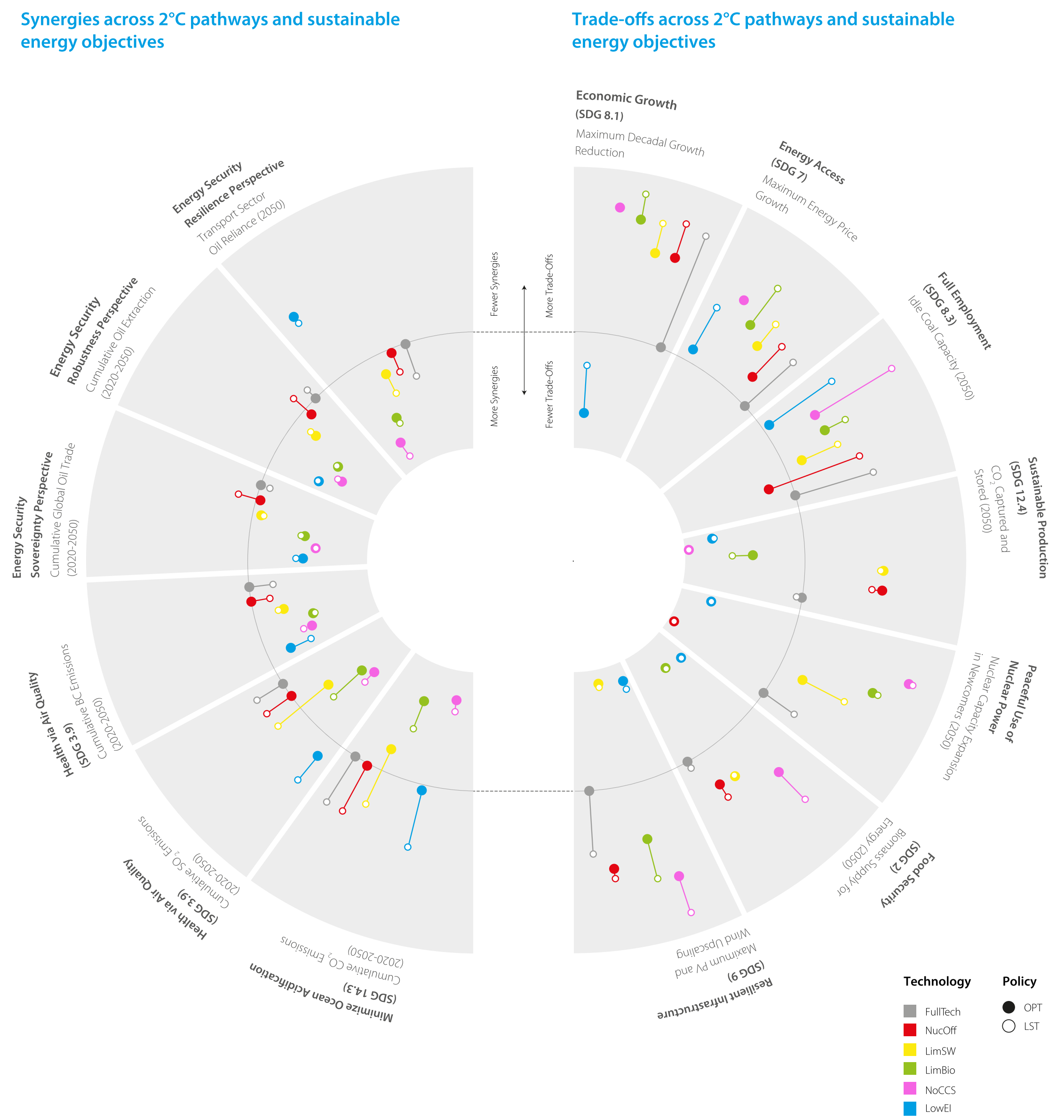

Figure 5. Percentage changes in SD risk dimensions that can be linked to a set of SDGs and other sustainable energy objectives in constrained 2 °C pathways relative to optimal pathways (assuming immediate mitigation with full availability of mitigation technologies and conventional energy demand growth). The different shapes denote different short-term climate policy stringencies while the different colours denote different technology cases (see table 3). As the figure aims at showing trends in synergies and risk trade-offs of alternative clusters of 2 °C pathways rather than an exact quantitative analysis, results are plotted in logarithmic scale (see table S4 for the underlying data).

challenged on these grounds (Fuss *et al* 2014, Smith *et al* 2016).

In a world which is increasingly unlikely to develop along 'optimal' scenario trajectories, an informed public debate about synergies and risk trade-offs implied by alternative clusters of constrained 2 °C pathways is key for identifying those which are socially acceptable. For example, current INDCs at best add up to emission trajectories similar to those 2 °C pathways with low short-term ambition ('LST' scenarios, see table 3)[10]. According to figure 5, these pathways (presented as circles) not only lead to fewer co-benefits compared to optimal 2 °C pathways (except for cumulative BC emissions and transport sector oil reliance) but also to significantly higher mitigation risk levels, particularly in socioeconomic dimensions—with higher risks of not meeting those SDGs related to economic growth, energy access, job preservation, food security and resilient grid infrastructure (see also figure S7).

When a technology constraint is added, only the risks specific to that technology can be lowered (e.g. reduced nuclear proliferation risks for scenarios with no new nuclear capacity or fewer grid integration challenges for scenarios with limited potential for solar and wind energy, see also figures S8 and S9). The other risk levels are exacerbated, particularly for those SDGs

[10] See http://infographics.pbl.nl/indc and http://climateactiontracker.org/global.

that relate to economic growth, job preservation, resilient infrastructure, and ocean acidification. This is particularly obvious for scenarios with limited global potential of bioenergy in which the risks related to bioenergy expansion are lower (including environmental effects related to BECCS deployment) but the risks of not meeting socioeconomic SDGs are significantly higher (see green circles in figure 5). Limiting the global use of bioenergy to 100 EJ per year by 2050—widely believed to be more sustainable (Creutzig *et al* 2014)—hence introduces a trade-off with socioeconomic objectives for weak short-term climate policies (see green circles in figure 5).

While there are uncertainties around acceptable levels of bioenergy deployment, the development and deployment of CCS technology is lagging behind expectations (IEA 2009), despite its important role in keeping mitigation costs at relatively low levels (Edenhofer *et al* 2014a). Our results highlight two things: first, those models that are flexible enough to compensate for the unavailability of CCS can only do so with increased upscaling requirements for other low-carbon technologies and related SD risks (see pink circles in figure 5). This also implies high near-term mitigation requirements with associated co-benefits. Second, the absence of CCS seriously questions the achievability of the 2 °C target in a world with delayed climate action and therefore threatens the climate SDG itself—only two models can report results for the combination with weak short-term climate policies.

In contrast, 2 °C pathways with lower energy demand growth generally entail a substantial reduction in SD risk levels (blue shapes in figure 5). This confirms results from a bottom-up assessment of the wider SD implications of technology-specific studies from a cross-sectoral perspective (von Stechow *et al* 2015). While these scenarios typically do not feature many additional co-benefits due to lower supply-side transition requirements, achieving lower energy demand growth has considerable synergies with the SDG agenda related to economic growth, food security, resilient grid infrastructure as well as with the peaceful use of nuclear energy. Delaying mitigation in scenarios with low energy demand growth only entails moderate risk increases—although some co-benefits are reduced and more coal capacity is likely to be retired early. Pursuing aggressive energy efficiency improvements across all sectors and rethinking high-energy lifestyles therefore seems essential to increase synergies and keep the trade-offs across SDGs manageable in a world that is characterized by multiple constraints. Unfortunately, model inter-comparison projects have not yet analyzed the combination of technology constraints and low energy demand growth pathways, which is a promising research area to better understand synergies between SDGs. Future research should also ensure that mitigation scenarios are consistent with minimum thresholds of energy demand necessary to satiate basic human needs (see discussion in SI section 2).

This letter has analyzed the changes in SD risks across alternative 2 °C pathways. These effects depend to a great extent on the development context, i.e., assumptions about baseline developments (Moss *et al* 2010, O'Neill *et al* 2014). To circumvent this potential caveat, the analysis used AMPERE data that stands out in its comprehensive effort to harmonize future socio-economic drivers of SD across models in the baseline scenarios: e.g., regional-level gross domestic product (GDP), population, and energy demand growth. This makes the results more comparable across models but begs the question of how the results would have changed for alternative assumptions beyond changes in energy demand growth. Research can and should build on alternative baseline developments as expressed by the 'shared socio-economic pathways' (O'Neill *et al* 2014) that will soon be published even though important, non-trivial discussions remain on how SDGs can be adequately built into these baselines (O'Neill *et al* 2015).

Indicators that were used to track the changes in SD risks are only rough and sometimes very rough approximations of individual SDGs. There is no doubt that individual models—particularly those coupled to a detailed agro-economic and land-use model—could already provide better indicators, such as for water availability and ecosystem impacts which are important concerns in stringent mitigation pathways (see SI section 3.1.1). However, these have not yet been analyzed in a multi-model study (von Stechow *et al* 2015). We believe that such inter-model comparison results are crucial for a meaningful public debate about SD risks.

Another important caveat of the analysis is that we focus on 2050 and the preceding decades when looking at the implications of alternative 2 °C pathways for SD risk dimensions. The risks of some 2 °C pathways, however, only unfold later in that century when some particularly risky negative emissions technologies, such as BECCS, are being deployed at large scale to compensate for lower mitigation efforts in the first decades and residual GHG emissions in other sectors (Fuss *et al* 2014, Smith *et al* 2016). For illustrative purposes, figures S10 and S11 show how mitigation risks change from 2050 to 2080 for scenarios with substantially different amounts of negative emission requirements. Since the AMPERE scenario specifications do not allow for a meaningful comparison across scenarios with low or high amounts of negative emissions, we use the amount of radiative forcing overshoot to cluster scenarios with respect to their dependence on negative emissions (also used in the WGIII AR5 scenario database, see Krey *et al* 2014). It shows that the magnitude of the mitigation risk levels can change substantially over time for those dimensions that are related to negative emission technologies such as CCS and bioenergy deployment.

Our analysis points to important future challenges: first, the chosen indicators do not represent all SDGs as some touch on socio-cultural and institutional aspects which are challenging—if not impossible—to represent in an economic model framework (see SI section 2). Second, the changes in the indicators across scenarios are merely indicative for the change in risks to meet the related SDGs and sustainable energy objectives because there are many more relevant drivers that cannot be analyzed based on the available scenario data. Third, many relevant issues play out at lower geographic and time scales which are difficult to represent adequately in global-scale integrated models. For example, food security is driven by many socioeconomic drivers both on global and local scales and bioenergy expansion represents but one of those (Tscharntke *et al* 2012). And according to Creutzig *et al* (2012), the models are not (yet) suitable for operationalizing important global SD dimensions of bioenergy supply such as the socioeconomic convergence across different countries. Nevertheless, we argue that the indicators used in this letter are relevant for evaluating additional pressure on the energy-economy-climate system from additional constraints as represented in the models. As such, they supply important information from internally consistent model frameworks taking into account inter-sectoral and inter-regional interactions (von Stechow *et al* 2015 and SI section 1).

We provide this early contribution to a public debate on the relationship between the international climate policy and the SDG agendas based on existing multi-model scenario data that was not specifically developed for this particular purpose. This stimulus seems important because results from model inter-comparisons that are tailored towards the SDG-climate nexus will not be published for some years. Only by working with the available data can we start discussing relevant (risk) trade-offs and synergies. Based on our analysis, we argue that SD considerations are central for determining socially acceptable climate policies and that the prospects of meeting other SDGs need not dwindle and can even be enhanced for some goals if appropriate climate policy choices are made. Moreover, experiences and caveats of this analysis can help guide future research efforts at a relevant moment in time when new model comparison exercises are being designed. For example, to remain policy-relevant, SDG-focused multi-model comparisons will need to address inequality, poverty, and basic human needs as major drivers of the policy process much more adequately. This requires a serious discussion, e.g., on how to deal with the coarse regional disaggregation in the integrated modelling frameworks. Equally, successful efforts to address SDG-relevant issues in one model, e.g., for the analysis of water availability or ecosystem impacts (see SI section 2), will need to be lifted into a multi-model context.

5. Conclusion

Until now, no multi-model study has been used to systematically analyze the changes in SD risks implied by stringent mitigation scenarios and evaluate them across a set of SDGs. This letter addresses this research gap by analyzing a comprehensive set of alternative clusters of 2 °C pathways consistently formulated across many integrated models from the AMPERE model inter-comparison study, drawing on publicly available scenario results to calculate indicators for global SD risks. We shed light on the implications of alternative clusters of 2 °C pathways for meeting a set of energy-related SDGs and other sustainable energy objectives and to inform the public debate about the synergies and trade-offs across the international climate policy and the SDG agendas.

Our analysis shows that the near-term choice of 2 °C pathways has implications for the extent of synergies and trade-offs across energy-related SDGs in the medium term. Given current trends in emissions and technology deployment, we argue that mitigation pathways are likely to be characterized by multiple constraints. But adding limits on the availability of specific mitigation technologies on top of weak short-term climate policies decreases synergies and locks in substantial trade-offs across environmental and socio-economic objectives. From an SDG perspective, the challenges of meeting other sustainable energy objectives substantially change with the way the climate SDG will be met. In some cases, meeting the 2 °C target is even threatened itself. Achieving low-energy demand growth, e.g., through aggressive energy efficiency improvements, helps to manage these trade-offs and attain multiple energy-related SDGs together. We find the greater the constraints on flexibility in meeting the 2 °C target, the higher the risks of not meeting other SDGs and the flexibility to manage these risks. Governments at all levels need to be informed about such implications of their collective decision for the attainability of global SDGs. This could avoid additional pressures on the sustainability of each region's development pathway.

After COP21, decision makers need to rethink their commitment to the SDG agenda, given that the short-term ambition for mitigation action falls short of the mitigation efforts consistent with staying below 2 °C in a cost-effective way. According to our results, this is likely to decrease co-benefits and increase the risks for attaining energy-related SDGs and other sustainable energy objectives. Since many of these SD risks are best dealt with at the global level, however, they might be good entry points into additional incentives for international cooperation. We suggest that the review of INDCs should provide for an assessment of policies at all scales to monitor global risks for non-climate sustainability objectives that arise from specific global mitigation pathways. Monitoring these risks could avoid unintended consequences (which might even delegitimize the 2 °C target), finding new entry points for global cooperation and providing rationales for ramping up mitigation ambition in the short to medium term.

Future research should extend the current system boundaries and, based on a comprehensive review of model literature on the climate-SDG nexus, establish indicators that help evaluate integrated policies addressing multiple SDGs in a unified framework. This would be a prerequisite for model inter-comparison projects with a focus on the interactions across multiple SDGs that could result in meaningful and robust results for better decision making. Climate policy will not be successful unless it seriously considers other policy objectives and therefore wider SD implications. Dividing the huge effort of achieving more sustainable development pathways into isolated policy problems will fall short of reaping synergies and successfully managing trade-offs across the many SDGs.

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Annex 2

Stechow C von, Minx JC, Riahi K, Jewell J, McCollum DL, Callaghan MW, Bertram C, Luderer G, Baiocchi G (2016) - Supplementary Information

Table of Contents

The supplementary information (SI) is structured as follows: SI section 1 provides a brief introduction into energy-economy-climate models, their differences and the rationale for model inter-comparison projects. SI section 2 gives an overview of important limitations of integrated models to address implications for some non-climate sustainability objectives. SI section 3 explains the link between a set of energy-related SDGs and other sustainable energy objectives, SD risks and associated indicators used in the analysis. SI section 4 lays out the main advantages of the model inter-comparison project AMPERE for such analysis. Supplementary figures and data are shown in SI section 5.

1 Integrated energy-economy-climate models

Integrated energy-economy-climate models, also often referred to as Integrated Assessment Models (IAMs), are computer-based tools to better understand the interactions between the economy, energy (in physical and economic terms) and often land-use systems as well as their effects on climate change. To explore the implications of alternative pathways in a range of plausible environments, they integrate insights from different disciplines and draw on models of both biogeophysical and human processes over long time horizons (Hourcade *et al* 2006, van Vuuren *et al* 2009, Edenhofer *et al* 2014). For example, they use information about energy resources, technologies, and investments as well as (land-use) emissions. The scenario results on which this letter's analysis is based are derived from seven different integrated energy-economy-climate models that took part in the AMPERE project (see SI section 4). They span a diversity of modelling approaches with respect to functional structures and parametric assumptions (Riahi *et al* 2015). Table S1 summarizes some of the main differences across the different models to the extent that they are relevant for our analysis. Please refer to Riahi *et al* (2015), the AMPERE website (http://ampere-project.eu) and the AMPERE scenario database for further information on the individual models and the scenario results they supplied.

The IAM community regularly organizes model inter-comparison projects in which efforts are made to harmonize key input parameters and to make model outputs comparable (Kriegler *et al* 2015b, Weyant *et al* 2006). As differences persist, a range of outcomes is plausible (Kriegler *et al* 2015a). To understand which results are robust across different models, we follow the approach of comparing results from multiple models in this letter. To circumvent climate system uncertainties with respect to the temperature response due to a given GHG emission scenario, the integrated models considered here usually calculate mitigation scenarios whose emission pathways meet different atmospheric CO_2eq concentrations or carbon budgets by 2100. The uncertainty reflected in their results (represented by the ranges in figures 1-4 and S3-S11) is hence distinct from the uncertainty of the change in the global temperature due to different emission scenarios (see Section 6.3.2.6 in Clarke *et al* 2014). The models analyzed here belong to a type of IAM that is based on cost-effectiveness analysis (CEA) and has to be differentiated from cost-benefit analysis (CBA)-based IAMs which are more controversial, e.g., in their attempt to determine optimal climate goals (Edenhofer *et al* 2014).

Also due to this coordinated research effort, the scenario results have been an important contribution to the IPCC WGIII (e.g., Fisher *et al* 2007, Fischedick *et al* 2011, Clarke *et al* 2014) and other global environmental science assessments (GEA 2012, UNEP 2014). Many of the widely held views about the requirements to meet the 2°C target stem from their insights, e.g. the GHG emissions reductions goals of 80-95% in developed countries below 1990 levels by 2050 (Knopf and Geden 2014).

Table S1. Key characteristics and representation of multiple sustainability objectives for the global integrated model frameworks used in the analysis (partly derived from Krey *et al* 2014, and von Stechow *et al* 2015).

Model name	Model type	Metric for climate change mitigation costs	System boundaries	Non-climate sustainability objectives covered	References for model documentation
DNE21+	Energy system partial equilibrium model – intertemporal optimization	Energy system cost mark-up	Energy, climate	Air pollution, energy security	(Akimoto *et al* 2012, Sano *et al* 2015, 2012, Wada *et al* 2012)
GCAM	Energy system partial equilibrium model – recursive dynamic simulation	Area under marginal abatement cost curve, energy system cost mark-up	Energy, land-use change, agriculture, forestry, climate, hydrology, some adaptation (not comprehensive)	Energy access, food, water, air pollution, energy security	(Calvin *et al* 2014, 2013, 2009, Clarke *et al* 2007)
IMAGE		Area under marginal abatement cost curve, energy system cost mark-up	Energy, land-use change, agriculture, climate, hydrology, some adaptation (not comprehensive)	Energy access, food, water, air pollution, biodiversity loss, energy security	(Bouwman *et al* 2006, Lucas *et al* 2013, van Ruijven *et al* 2012, Vliet *et al* 2013)
POLES		Area under marginal abatement cost curve, energy system cost mark-up	Energy, land use change	Air pollution, energy security	(Dowling and Russ 2012, Griffin *et al* 2013, IPTS 2010)
MESSAGE-MACRO	Systems engineering energy system model coupled with macroeconomic generable equilibrium model – perfect foresight, optimization	GDP & consumption loss, energy system cost mark-up, area under marginal abatement cost curve	Energy, aggregated representation of land-use GHG emissions, climate, water for energy	Energy access, water, air pollution/health, energy security	(McCollum *et al* 2013, Messner and Schrattenholzer 2000, Pachauri *et al* 2013, Rao and Riahi 2006, Riahi *et al* 2007)
REMIND	Optimal growth general equilibrium model – perfect foresight, optimization	Welfare change, GDP & consumption loss, energy system cost mark-up	Energy, aggregated representation of land-use GHG emissions, climate,	Air pollution, energy security	(Bauer *et al* 2011, Leimbach *et al* 2010, 2009, Luderer *et al* 2013b, 2011)
WITCH		Welfare change, GDP & consumption loss, energy system cost mark-up	Energy, aggregated representation of land-use GHG emissions, climate, climate damages and adaptation	Air pollution, energy security, adaptation	(Bosetti *et al* 2009b, 2006, De Cian *et al* 2011, Tavoni *et al* 2013)

2 Limitations of integrated models to address implications for non-climate sustainability objectives

In the WGIII AR5, alternative mitigation scenarios based on integrated models were mainly used to analyze (i) the technological and energy-system requirements of staying below a pre-determined GHG concentration threshold (such as decarbonization rates in a given period) and their regional interactions, (ii) the probability of exceeding that threshold, and (iii) the associated aggregate macroeconomic costs on global or regional levels (Bruckner *et al* 2014, Clarke *et al* 2014). Only a fraction of the studies that were assessed have also analyzed (i) the potential co-benefits for non-climate sustainability objectives (such as energy access, energy security and air quality) and (ii) the risks for non-climate sustainability objectives (such as land and water availability and biodiversity). But these studies either focused on specific co-benefits and SD risks or build on individual models (von Stechow *et al* 2015).

Similar to the challenges of aggregating local co-benefits on a global scale (von Stechow *et al* 2015), mitigation risks are challenging to quantify, let alone monetize, on a global level. Recently published literature hence focuses on technology-specific indicators for global mitigation risks, such as those associated with bioenergy (see, e.g., Bonsch *et al* 2016, Humpenöder *et al* 2014, Creutzig *et al* 2012b, 2012a), comparing scenario results with empirical evidence of energy technology transition processes in the past (e.g., Guivarch and Hallegatte 2013, Wilson *et al* 2013); or outlining the socioeconomic challenges of meeting international agreements given the discrepancy between current trends and long-term requirements (Luderer *et al* 2013c, Rogelj *et al* 2013a, 2013b, 2010, UNEP 2014, Luderer *et al* 2013a, Kriegler *et al* 2015b, Rogelj *et al* 2015, Kriegler *et al* 2013).

Fully understanding the implications of alternative 2°C pathways for non-climate sustainability objectives would require modelling frameworks that can simultaneously optimize multiple objectives across sectors, regions and generations taking into account institutional settings. There are thus far, however, no modelling frameworks available that can optimize development pathways across that many objectives – also because the determination of damage functions is also highly value-laden (Ackerman and Heinzerling 2002, Lackey 2001, Pindyck 2013). This is why we draw on results from integrated models whose strength it is to analyze long-term mitigation pathways across sectors and regions in a consistent way although integrated models do neither optimize over other objectives nor measure the levels of sustainability objectives directly (for exceptions, see section 4 in von Stechow *et al* 2015). Hence, the interpretation of integrated model results as risk indicators for non-climate sustainability objectives provides, at best, a reasonable approximation of the interrelation between mitigation and multiple other objectives at the global level. Given the current little previous research on the impacts of climate change mitigation on non-climate sustainability objectives, this exercise already yields interesting new results.

Due to their global scope and coverage of the economy, energy, climate as well as land-use systems, integrated models inevitably are limited in the level of detail they can represent in other dimensions. For example, there is some critical literature on the implications of the structural set-up of and assumptions in integrated models for SD more broadly, such as for human development and inequality (e.g., Lamb and Rao 2015, Steckel *et al* 2013, Sathaye *et al* 2011, Stanton 2010). In the following paragraphs, we address some of these limitations to the extent they pertain to the models' ability to analyze the implications for non-climate sustainability objectives. Some of these limitations are briefly mentioned in the discussion of the main text while others are discussed in SI section 3. But rather than pointing to new insights, this section aims at providing an overview by structuring existing model critique into issues around (i) economic aggregation, (i) spatial aggregation, as well as (iii) institutional settings.

Like other economic models, integrated assessment models often assume homogeneity across economic agents by relying on a representative household rather than differentiating income groups or along other socio-economic criteria. This makes any analysis of distributional consequences within countries very challenging. Many climate policies have been identified as increasing equality challenges through, e.g., higher energy prices (see SI section 3.1.3), higher food prices (Wise *et al* 2014, Tadesse *et al* 2014, von Braun *et al* 2008) or indirectly through higher consumer prices (Fullerton and Metcalf 2001, Bovenberg and van der Ploeg 1994). However, integrated models can only take this into account if coupled to other models that consider, e.g., different income groups and/or rural and urban populations (van Ruijven *et al* 2012, Cameron *et al* 2016, Pachauri *et al* 2013, Daioglou *et al* 2012, Krey *et al* 2012) and skill levels (Guivarch *et al* 2011). Unless a model study is specifically designed to consider such distribution effects, multi-model results, such as those of AMPERE, are not suitable to analyze effects on SDG 1, 5 or 10.

Analyzing distributional effect among countries (SDG 10) is challenging due to the coarse spatial disaggregation of integrated models. The models only represent broad major economies, such as USA, China, Brazil and Japan as individual countries, while aggregating others to up to continental-scale macro-regions (Krey *et al* 2014). Analysis of distributional effects hence focuses on an inter-regional perspective and is only meaningful for alternative assumptions on international effort sharing regimes (Ekholm *et al* 2010, Elzen *et al* 2008, Elzen and Höhne 2008, Tavoni *et al* 2013, 2015, Aboumahboub *et al* 2014, Luderer *et al* 2012). In addition, models vary in their sectoral resolution, and only represent a limited number of sectors explicitly. This makes any analysis of technological issues related to spatial heterogeneity, such as infrastructure build-up and urban transformation (SDGs 9 and 11), highly challenging or even impossible.

With their focus on the technological and macroeconomic aspects of energy transitions, integrated models have very limited abilities to capture social phenomena and structural changes (Sathaye *et al* 2011). At the same time, there are many sustainability objectives for which institutional and social developments are much more decisive than the structure of the energy system, such as for the provision of basic services health, education and justice (SDGs 3, 4 and 16). This makes integrated models poorly equipped to address these SD dimensions.

Considering the models' limited ability to consider different income groups for different geographical characteristics and institutional settings, "an explicit representation of the energy consequences for the poorest, women, specific ethnic groups within countries, or those in specific geographical areas, tends to be outside the range of current global model output" (Sathaye *et al* 2011, p 752). From the literature, we know, however, that there is a minimum energy requirement to satiate basic human needs (Pachauri and Spreng 2004, Steinberger and Roberts 2010, Lamb and Rao 2015) unless economic growth is assumed to break with historical trends (Steckel *et al* 2013). According to Lamb and Rao (2015), this threshold is approximately 30 GJ/year per capita. While the models typically do not explicitly take into account energy demands for basic needs related to cooking, heating, health and other infrastructure and services, their final energy pathways in mitigation scenarios still largely respect the 30 GJ/yr threshold. For instance, only two out of the seven models project final energy supply levels in mitigation pathways for India in 2050 that are below this level for reference assumptions on final energy (see figure S1). At the same time, as highlighted in the main text, the assumptions for lower energy demand growth need not additionally affect development outcomes but assume lower energy intensity (lowEI) through higher energy efficiency and, e.g., the viability of more compact, public transit-friendly urban areas (Riahi *et al* 2015).

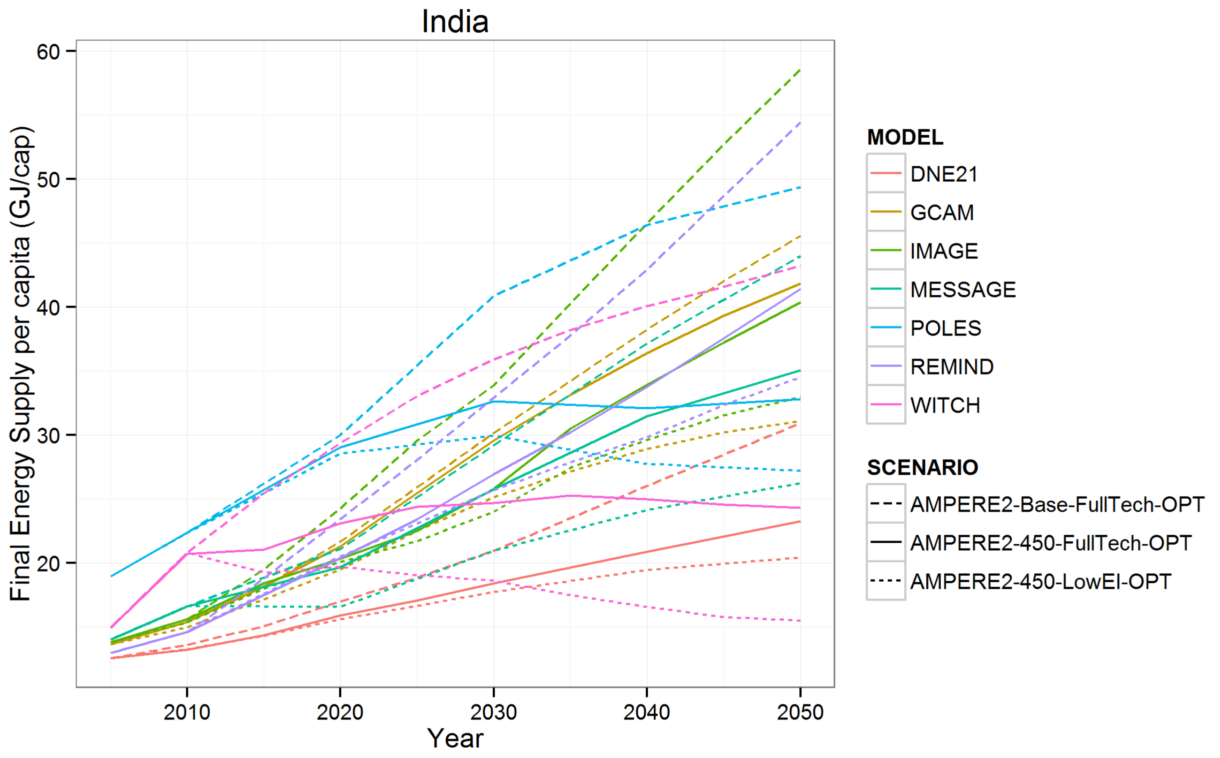

Figure S1. Final Energy Supply (in GJ) per capita for baseline scenarios and 2°C pathways with conventional and low energy demand growth assumptions

4 Linking energy-related SDGs and other sustainable energy objectives to SD risks and associated indicators based on integrated model results

This section gives some background on the choice of indicators calculated from model variables (column 1 in table 2) that approximate SD risks (column 2) for energy-related SDGs and other sustainable energy objectives (column 3), used for the analysis of alternative 2°C pathways in the main text. The choice of SD risk dimensions discussed in this letter was guided by three criteria:

1. Discussion of risk dimensions and related quantitative indicators in the literature (see table 1);
2. Possibility to link to energy-related SDGs (or other sustainable energy objectives) covering all three SD dimensions: economic, environmental and social (see SI section 3.1).
3. Public availability of model variables (from which suitable indicators can be calculated, see SI section 3.2) in the AMPERE database to serve transparency purposes (see SI section 4);

SI section 3.1 lays out in some detail the avenues by which mitigation can lead to increased or decreased risks for non-climate sustainability objectives and how the different SD risks can be linked to a set of energy-related SDGs and other sustainable energy objectives. It should be noted that many risk dimensions in fact have an impact on several SDGs – both in negative and in positive ways (see figure S2 for an overview) and choosing a single SDG to represent one risk dimension means simplifying these complex interlinkages. SI section 3.2 then explains how the chosen indicators for these risk dimensions can be calculated from integrated model variables reported in the AMPERE scenario database.

4.1 Linking SD risks to energy-related SDGs and other sustainable energy objectives

This section discusses the second criterion and reviews literature on the basis of which the link between SD risk dimensions and SDGs and other sustainable energy objectives can be established. This section is partly based on the Supplemental Material from von Stechow *et al* (2015) which reviews recent literature on the co-effects of mitigation measures in the energy supply as well as different energy demand sectors. As in von Stechow *et al* (2015), the discussion of co-effects in the agriculture, forestry and other land-use (AFOLU) sector is limited to the co-effects of increasing bioenergy supply – mainly because this was not a focus of the AMPERE project.

As discussed in SI section 2, integrated models have some limitations in their ability to address some non-climate sustainability objectives, such as distributional effects. This is why this section does not discuss links to some important SDGs, such as SDG1 (“end poverty in all its forms everywhere”) and SDG 10 (“reduce inequality within and among countries”). To some extent, however, the chosen set of indicators implicitly speaks to the aims of poverty and inequality reduction, because:

i) food security concerns are most problematic for the urban poor (Ahmed *et al* 2009);
ii) air pollution disproportionally impacts the poor in dense urban areas (Frumkin 2002);
iii) not achieving energy access goals threatens the associated benefits in terms of local economic development, educational benefits, and income generation (SI section 3.1.6);
iv) economic growth reduction makes poverty reduction more challenging (SI section 3.1.4);
v) jobs at risk in the fossil fuel industry affect the unskilled most (Fankhauser *et al* 2008).

4.1.1 *Bioenergy expansion and food security (SDG 2)*

Achieving food security is an important aspect of SDG 2 but may be challenging to achieve in the light of climate change. On the one hand, stringent mitigation is likely to avoid the worst impacts of climate change which endangers sustainable food production systems (Porter *et al* 2014). On the other hand, an increased amount of biomass demand for energy purposes required in many mitigation scenarios may induce competition on arable land (except for bioenergy derived from residues, wastes or by-products) (Haberl *et al* 2014) with resulting impacts on food production and security (Ewing and Msangi 2009, Finco and Doppler 2010, Tilman *et al* 2009).[1] In a study that compares the effect of 100 EJ of lignocellulosic bioenergy to the potential climate impacts of a high-emission scenario on crop yields, the benefits of bioenergy for mitigation outweigh the adverse impacts in terms of food prices increases (Lotze-Campen *et al* 2014). But with higher amounts of bioenergy demand, the risks are likely to increase: Bioenergy production and the resulting land competition have implications for many non-climate sustainability objectives, such as reducing water availability (SDG 6.4), displacing communities and economic activities (SDG 8), driving deforestation (SDG 15.2), reducing soil quality (SDG 15.3), and impacting biodiversity (SDG 15.5) (Amigun *et al* 2011, Borzoni 2011, Chum *et al* 2011, Creutzig *et al* 2013, German and Schoneveld 2012, Hall *et al* 2009). Most integrated models are not yet well equipped to study these effects, but preliminary research exists, e.g., on water and biodiversity impacts (Bonsch *et al* 2016, De Fraiture *et al* 2008, PBL 2012, van Vuuren *et al* 2015). The main potential co-benefits seem to be related to improved access to energy services (SDG 7), job creation (SDG 8.3), and energy security (Amigun *et al* 2011, Arndt *et al* 2012, Duvenage *et al* 2012, Finco and Doppler 2010, Huang *et al* 2012, Leiby and Rubin 2013, Tilman *et al* 2009). More generally, due to the different bioenergy sources as well as to the specificities of the areas where bioenergy is produced, SD impacts from bioenergy are context-, pace- and size-specific (Bustamante *et al* 2014, Creutzig *et al* 2013, Popp *et al* 2011, Smith *et al* 2014b).

4.1.2 *Air pollutant concentration and health via air quality (SDG 3.9)*

One important aspect to ensure healthy lives is to substantially “reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination” (SDG 3.9). SO_2 and NOx, for instance, contribute to the acidification of water bodies (SDG 6.3) and soil (SDG 15.3) and NOx to eutrophication – a threat to biodiversity (SDG 15.5) (Hertwich *et al* 2010, Rockström *et al* 2009). Exposure to particulate matter (PM), emitted directly as BC and OC or formed from SO_2 and NOx, leads to premature deaths of more than 3.5 million people per year (Lim *et al* 2012, Smith *et al* 2014a). More than 80% of the global population is still exposed to PM concentrations that exceed the WHO recommendations of 10 µg/m3 $PM_{2.5}$ (Rao *et al* 2013). But the local health effects can differ substantially depending, for example, on the efficiency of the combustion process, the place of the emission source, the scrubber technology, the downwind population concentration as well as the background pollution from other sources (Bell *et al* 2008, Smith and Haigler 2008, Sathaye *et al* 2011).

In addition to the reduced health effects of less air pollution and resulting water and soil pollution, reducing air pollutant emissions arising from energy supply also helps protecting and restoring the

[1] Some agroforestry plantation can contribute to food security while producing biomass resources (Smith *et al* 2014b).

sustainable use of marine and terrestrial ecosystems (SDGs 14 and 15). Even though some individual low-carbon energy technologies such as concentrated solar power tower technologies, some hydropower plants and CCS technologies show considerable pollution-related health and ecological effects – taking into account life-cycle emissions and thus accounting for emissions from material and fuel production, manufacturing, operation and decommissioning – Hertwich *et al* (2015) generally found significantly lower pollution-related indicators for renewable energy (RE) technologies (see discussion in SI section 3.1.6 on wind energy and PV). This co-benefit is mainly due to the reduction of co-emitted pollutants associated with the decarbonization of energy supply, which is nearly complete in 2050 for stringent 2°C pathways (Bruckner *et al* 2014, Clarke *et al* 2014, Riahi *et al* 2015). Integrated model studies indicate that there are significant co-benefits for a number of pollutants – up to 50/35/30/22% reductions by 2030 globally of SO_2, NOx, $PM_{2.5}$, and Hg emissions or concentrations relative to baseline scenarios (see von Stechow *et al* 2015 for a review).

Finally, methane emissions that contribute to the formation of tropospheric ozone with negative impact on crop yields (van Dingenen *et al* 2009) can be reduced in coal mining and gas and oil production (Bruckner *et al* 2014). Reducing fossil fuel use, particularly coal, and methane leakage reduction can mitigate near-term climate change and improve health and food security (Anenberg *et al* 2012, Shindell *et al* 2012).

4.1.3 Energy price growth and energy access (SDG 7)

SDG 7 aims at ensuring "universal access to affordable, reliable, and modern energy for all". This is a huge challenge since more than 1.3 billion people worldwide, especially in sub-Saharan Africa and developing Asia, lack access to electricity and over 2.5 to 3 million people are estimated to lack modern fuels for heating and cooking (IEA 2012, Pachauri *et al* 2013). Whilst improvements in energy access do not need to entail significant changes in GHG emissions (Pachauri *et al* 2013), climate policies are likely to increase energy prices, at least in the short term, due to carbon pricing, fuel switching and higher energy production costs from low-carbon energy technologies (Bertram *et al* 2015b, Bruckner *et al* 2014, Fischedick *et al* 2011, Jakob and Steckel 2014) which can result in higher challenges for achieving energy access objectives (van Ruijven *et al* 2012, Cameron *et al* 2016, Pachauri *et al* 2013, Daioglou *et al* 2012, Krey *et al* 2012, van Vuuren *et al* 2015).

Even though the global energy price index that was used for this letter (see SI section 3.2.2) is generally set to increase in mitigation scenarios with conventional energy demand growth assumptions, the effect on those without energy access today depends importantly on locally specific circumstances, such as the type of fuel used by different income groups, the distribution of the revenues from climate policy and the effectiveness of pro-poor policies that are in place today or could be implemented to complement climate policies (Casillas and Kammen 2010). In fact, a recent study shows that the costs of achieving energy access change with the stringency of climate policy but are even more sensitive to the way energy access policies are implemented (Cameron *et al* 2016).

The effects of energy prices on economic growth are not explicitly analyzed here because the macroeconomic effects of mitigation, including general equilibrium effects of changing energy prices, are captured to some extent by the integrated models (see below in SI section 3.1.4). To what extent higher energy prices are a concern from an inequality perspective depends on the distributional consequences, which cannot be derived from the AMPERE scenario database (see SI section 2). Since poorer households spend a higher proportion of their disposable income on energy needs, higher energy prices are a problem not just for those without sufficient energy access today (Moore 2012). While there is a regressive impact of higher energy prices in developed countries (Grainger and Kolstad 2010, Romero-Jordán *et al* 2016, Frondel *et al* 2015, Nelson *et al* 2011), the empirical evidence is mixed for developing countries (Jakob and Steckel 2014). Fuel taxes, for example, seem to be generally progressive in poor countries (Somanathan *et al* 2014).

In addition, higher energy prices are not only a concern for energy access goals, but also for health (SDG 3): Higher energy prices could adversely affect the ability of households to guarantee a certain level of consumption of domestic energy services (especially heating) or may place disproportionate expenditure burdens to meet these needs. Fuel poverty has a range of negative effects on the health and welfare of fuel poor households, such as an increase in excess winter mortality rates, excess morbidity effects, depression and anxiety (Clinch and Healy 2001). But these effects can be greatly reduced by mitigation measures in the buildings sector (Ürge-Vorsatz and Tirado Herrero 2012).

4.1.4 Consumption growth reduction and economic growth (SDG 8.1)

Sustaining economic growth is one of the core requirements to achieve a number of non-climate sustainability objectives, such as poverty reduction (Ravallion and Chen 1997, Rodrik 2008) and higher employment levels (Blanchard and Wolfers 2000, Crivelli *et al* 2012, McMillan *et al* 2014), and are reflected in SDGs 1 and 8. While the negative impact of stringent climate policy on aggregate measures of consumption growth is limited (see SI section 3.2.1), integrated models project higher transitional economic growth reductions in the decade after implementation of the climate policy (Bertram *et al* 2015b, Kriegler *et al* 2013, Luderer *et al* 2013a, 2013c). Because the effects in the short to medium term are of particular interest for achieving SDG 8.1, this letter’s focus is on transitional rather than aggregate long-term metrics of economic growth reductions as mitigation risk indicator.

4.1.5 Stranded fossil investment and full employment (SDG 8.3)

Achieving full and productive employment features as another sub-goal of SDG 8. While many mitigation measures potentially have a positive effect on gross job creation (such as energy efficiency measures in the housing and industry sectors as well as upscaling of RE, see below in SI section 3.1.6), the net effect of mitigation pathways on employment in the medium to long term remains disputed, considering all aspects of mitigation technologies (e.g., labor intensity and implications for job quality and skills) as well as trade, investment, innovation and general equilibrium effects (Babiker and Eckaus 2007, Böhringer *et al* 2013, Clarke *et al* 2014, Fankhauser *et al* 2008, Guivarch *et al* 2011). Yet, it is clear that many jobs in the fossil fuel industry (and the associated value chains) will be lost in the short term due to the energy system transition from carbon-intensive industries towards more low-carbon sectors (Fankhauser *et al* 2008).

Since it is difficult for policy makers to credibly commit to a climate policy trajectory, investors will find it challenging to make investment decisions consistent with long-term climate goals in a changing policy environment dominated by uncertainties about the possibility and extent of global cooperation on climate change mitigation (Brunner *et al* 2012). Accordingly, from 2005 through 2013, approximately 722 GW of new capacity was added to the global coal fleet and over 1,000 GW of coal power plant capacity is still proposed globally – despite a drop of 23% from 2012 numbers (Shearer *et* *al* 2015). Some experts speak about a 'renaissance of coal' (Steckel *et al* 2015). To avoid excess job losses (and the associated negative effects on overall economic output) when choosing climate policies, decision makers should be interested in minimizing the additional build-up of long-lived carbon-intensive infrastructure (such as coal power, see SI section 3.2) (Rozenberg *et al* 2014). This is because a large share of any new coal capacity built over the next decades would likely need to retire early to comply with the carbon budget consistent with the 2°C target – with the associated employment implications.[2] This is particularly important in emerging economies where most new capacity would be built (Bertram *et al* 2015a, Johnson *et al* 2015). Early retirement of thermal power plants also impacts power grid stability (Holttinen 2012) that is discussed in the next sub-section.

4.1.6 Wind & PV grid integration and resilient infrastructure (SDG 9)

Building resilient infrastructure features as SDG 9 to support economic development and human well-being. As described in SI section 3.2.7, adding large amounts of partially dispatchable and predictable RE capacity (e.g., wind energy and PV) in a short time is a challenge for power grids. The resulting technical and economic risks may even put public acceptance of RE at risk as can be observed in the public debate on the German 'Energiewende' (Frondel *et al* 2015, 2012). This is a concern from the perspective of many other SDGs on which higher RE deployment would have positive impacts:

- Replacing coal with wind and PV would be associated with a wide range of co-benefits as their pollution-related indicators are generally significantly lower (Hertwich *et al* 2015).[3] This would reduce the number of deaths and illnesses from air pollution (SDG 3.9), improve the water quality by reducing pollution (SDG 6.3) and contribute to "conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services" (SDG 15.1). This is also helped by the fact that the consumptive water use of wind energy and PV is small (Meldrum *et al* 2013).
- Higher deployment of wind energy and PV links directly to a sub-goal of SDG 7 (7.2: "increase substantially the share of RE in the global energy mix by 2030") because they can help promote off-grid access to energy services in countries with little central grid access. This is because research indicates that improved energy access by means of RE also stimulated local economic development in a number of developing countries (Goldemberg *et al* 2008, Walter *et al* 2011) and led to educational benefits and enhanced support for income generation in large parts of the developing world (Bazilian *et al* 2012, Kanagawa and Nakata 2007, Sokona *et al* 2012).
- Studies from China, Germany, Spain and the US found net job gains due to an increased share of RE with higher labour intensity (Cai *et al* 2011, Lehr *et al* 2012, Ruiz Romero *et al* 2012, Wei *et al* 2010). Similar results have been found for RE in the buildings sector (Lucon *et al* 2014). On the one hand, this may help achieving SDG 8, namely "higher levels of productivity of economies…through a focus on high value added and labour-intensive sectors" (SDG 8.3). On the other hand, RE, particularly PV, still relies on substantial public support, implying that some of the above adverse effects apply with respect to opportunity costs of using public funds and skilled

[2] As witnessed in Germany, even the prospect of climate regulation that would necessitate the retirement of rather old coal power plants led to a public debate and subsequent withdrawal of the initial proposal, based on (mainly unsubstantiated) arguments around potentially substantial job losses in particular regions and supplying industry (Oei *et al* 2015).

[3] It should be noted, however, that collisions of birds and bats with wind power plants are an important concern (Giavi *et al* 2014, Lehnert *et al* 2014, Marques *et al* 2014).

workers as well as trade and general equilibrium effects (see SI section 3.1.5) (Böhringer *et al* 2013, Frondel *et al* 2010, Lambert and Silva 2012).

- Finally, higher RE deployment in mitigation scenarios generally leads to lower energy imports (Criqui and Mima 2012, Jewell *et al* 2014, Kruyt *et al* 2009), a co-benefit for energy security.

4.1.7 Energy security

Energy security vulnerabilities can be characterized by three different perspectives: sovereignty (risks primarily arise from foreign actors), robustness (risks can be calculated and avoided) and resilience (risks are uncertain and systems must be designed to be able to recover from disruptions) (Cherp and Jewell 2014, 2011). For the purposes of this letter, we focus on oil security since it is the most vulnerable fuel globally with most countries dependent on imported oil from a limited number of exporting countries, the most acute scarcity concerns (both real and perceived) and it faces virtually no substitutes in the transport sector (Cherp *et al* 2012). In fact, the inflexibility of the oil system is one of the reasons it has been one of the main foci of energy security strategies, in particular with the creation of the International Energy Agency (IEA) after the 1970s oil crises.

For our analysis, we consider one indicator for each perspective on oil security: cumulative oil trade to represent sovereignty risks (see SI section 3.2.10); cumulative oil extraction to represent robustness concerns (see SI section 3.2.11); and non-oil use in the transport sector to represent the resilience perspective (see SI section 3.2.12). This admittedly neglects energy security risks arising from critical infrastructure vulnerabilities (Farrell *et al* 2004) – except short-term reliability concerns from variable renewables (see SI section 3.2.7) (Johansson 2013) – but infrastructure is not very well depicted in integrated models so is not the best tool to explore these types of risks (see SI section 2).

4.1.8 Peaceful use of nuclear power

Many mitigation scenarios depict tremendous growth in nuclear energy – up to four times current levels by mid-century (Kim *et al* 2014). The risks associated with nuclear energy include accidents, physical security – nuclear materials falling into the wrong hands – and proliferation – the spread of nuclear weapons and fissile material to new countries (von Hippel *et al* 2012).[4] Similar to the relationship with energy intensity (EI), the less energy produced from nuclear, the lower each of these risks is. The accident risk is calculated in terms of incidents per reactor years; thus all else being equal, increasing the nuclear power fleet increases the risk of accidents. Yet, many integrated models do not distinguish between types of nuclear power plants, let alone which safety mechanisms are implemented where so the only way to analyze this would be assume the same accident risk for the full nuclear fleet. Thus for the purposes of our analysis we focus on physical security and proliferation risks related to nuclear power (see SI section 3.2.5).

[4] Some epidemiological studies on the health effect of radioactive material handling find a higher childhood leukemia of populations living within 5 km of nuclear power plants (Heinävaara *et al* 2010, Kaatsch *et al* 2008, Sermage-Faure *et al* 2012). Nuclear energy also reduces pollution-related indicators compared to coal with positive health effects (Hertwich *et al* 2015) making the net effect on health very challenging to assess.

4.1.9 Environmental risks of CCS chain and sustainable production (SDG 12.4)

Achieving environmentally sound management of chemicals and reducing their release to air and water to minimize their adverse impacts on human health and the environment features prominently in SDG 12. While CCS is an important mitigation technology, particularly because it can be coupled with bioenergy to produce negative emissions and thus increases the flexibility to reach stringent climate goals (Clarke *et al* 2014, Fuss *et al* 2014), high deployment of CCS increase the environmental concerns of fossil-fuel based power supply. On the one hand, the CCS process requires 16-44% of additional energy (Corsten *et al* 2013), thereby increasing the fuel requirements and associated environmental impacts, such as ecological damage (SDG 15), higher mudslides risks, and water contamination (SDG 6.3) (Adibee *et al* 2013, Palmer *et al* 2010, Smith *et al* 2013). On the other hand, CO_2 capture requires a pure gas stream, reducing some air pollution from the power plant, such as SO_2 (Koornneef *et al* 2008). Investigating different CCS technologies for relevant life-cycle indicators, Hertwich *et al* (2015) find that, on balance, CCS leads to increases in PM, toxicity and eutrophication by 5-60% compared to modern coal and gas power plants. Many of these additional air pollutant emissions would also negatively impact health (SDG 3.9, see SI section 3.1.2) and marine ecosystems (SDG 14). If coal is substituted by biomass (to enable net negative GHG emissions via BECCS), Schakel *et al* (2014) find that the biomass supply chain and the combustion-related pollution are comparable to that of coal with respect to environmental and health impacts.

Most CCS technologies also significantly increase water withdrawal and consumption (up to 100%) due to efficiency penalties and additional process demands (Zhai *et al* 2011, Meldrum *et al* 2013) – with the latter causing ecological impacts (Verones *et al* 2010). There are also concerns about groundwater contamination due to CO_2 leakage (Apps *et al* 2010, Atchley *et al* 2013, Siirila *et al* 2012). As much as additional wind energy and PV helps alleviating concerns about water availability and quality, CCS may hence add to these (SDG 6.3). As discussed in SI section 3.2.4, there are substantial uncertainties attached to the hydrogeological characteristics and volumes of the geological reservoirs. For example, concerns about induced seismicity could potentially affect surface structures or simply alarm the population (Mazzoldi *et al* 2012). With open questions about the resilience of existing reservoirs (White *et al* 2014), higher CCS deployment may increase concerns about the resilience of the installed infrastructure (SDG 9).

On the positive side, retrofitting CCS can potentially alleviate the extent of stranded investment of coal-power plants (Johnson *et al* 2015). Successful deployment of CCS technologies could potentially preserve many jobs in the fossil-fuel industry (Fankhauser *et al* 2008, Wei *et al* 2010) – a contribution to achieving SDG 8.3 in the short term.

4.1.10 Peak atmospheric CO_2 concentration and minimization of ocean acidification (SDG 14.3)

Ocean acidification is an important global change problem and hence features as one sub-goal of SDG 14. While it is often analyzed together with impacts of climate change (IPCC 2014), future changes in ocean acidification are largely independent of the amounts of climate change but are mainly driven by CO_2 emissions (Cao *et al* 2007). As such, reductions in ocean acidification and associated aragonite saturation states (Ω_a) can also be regarded as a co-benefit of CO_2 emissions reductions primarily targeted at climate change mitigation (Joos *et al* 2011). High changes in pH and Ω_a adversely affect vulnerable marine organisms that build shells and other structures from aragonite (Orr *et al* 2005). For example, if atmospheric CO_2 is stabilized at 450 ppm, only 8% of existing coral reefs will be surrounded by water with pre-industrial saturation levels down from 98% (Cao and Caldeira 2008). These concentrations are surpassed by 2050 in some delayed 2°C pathways due to high concentration overshoot whereas pathways without negative emissions stay below that threshold. Whereas global mean temperature change mainly depends on cumulative CO_2 emissions (IPCC 2014), the response of pH and Ω_a is delayed in the ocean interior – highlighting the importance of 2°C pathways with low concentration overshoot to avoid irreversible damage (Mathesius *et al* 2015).

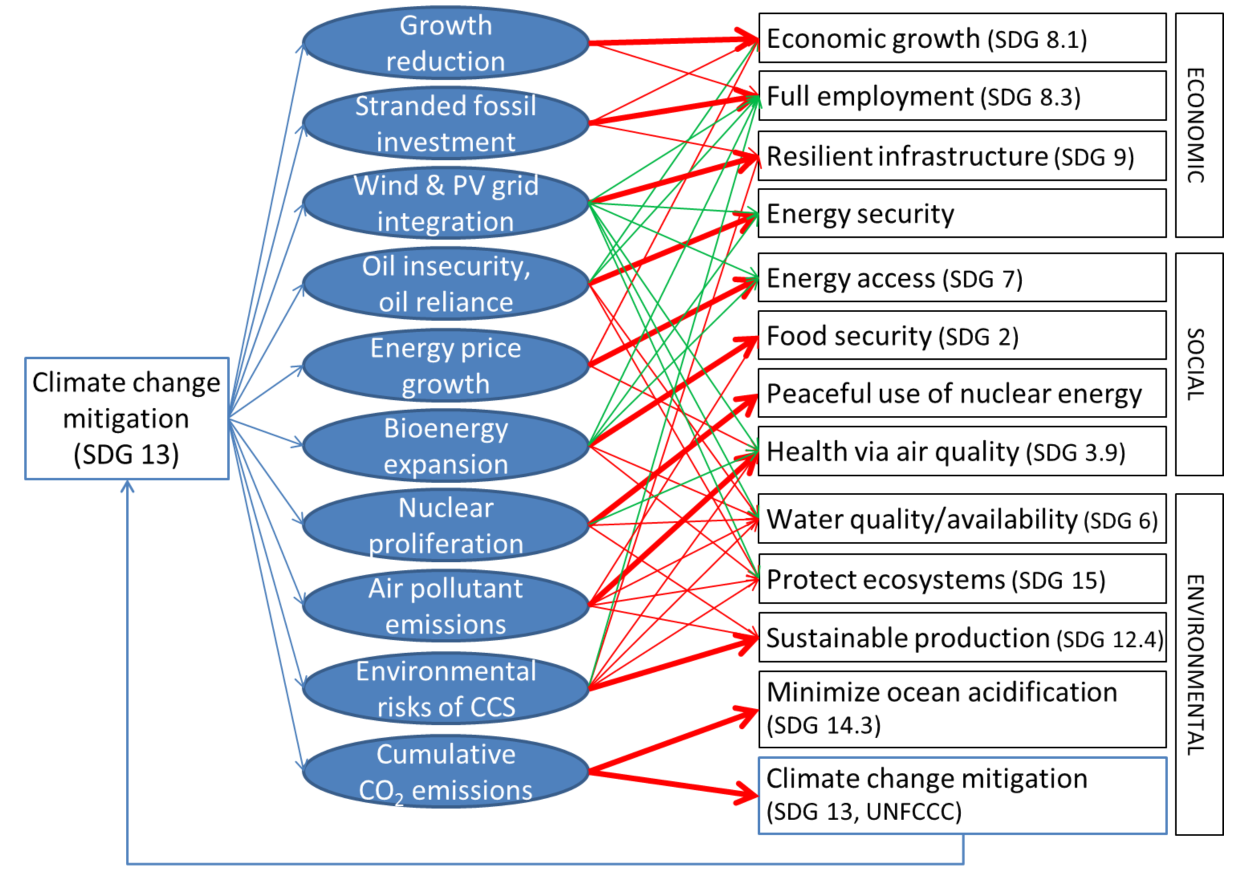

Figure S2. The SD risks were chosen (i) based on existing literature and such that (ii) associated indicators can be calculated from integrated model variables that are readily available from scenario results in the AMPERE scenario database to serve transparency purposes; and (iii) link directly to a set of energy-related SDGs and other multilaterally agreed sustainable energy objectives covering all three SD dimensions: economic, environmental and social.

4.2 Linking indicators calculated from integrated model variables to SD risks

All indicators for SD risks that are described in detail below – following the order of the indicators as they appear in figure 5 – show the difference between the value for each mitigation scenario and that for the baseline as a percentage of the baseline value (except for Figure 5 which compares alternative 2°C pathways to each other, see Table S.4 for the underlying data). The baseline is derived from the values of the "AMPERE2-Base-FullTech-OPT" scenario in the same model, unless otherwise stated. For the indicator for which baseline scenarios show values of or near zero (and hence does not lend itself to an analysis of relative changes), the following paragraphs introduce a reference value against which the values from mitigation scenarios are compared (see SI section 3.2.4).

4.2.1 *Maximum decadal consumption growth reduction*

While cost-benefit analyses (CBA) of climate change mitigation has been prominently discussed in climate economics (Stern, 2008), the approach has many drawbacks (as discussed, e.g., in Edenhofer *et al* 2014, Kunreuther *et al* 2014, Pindyck 2013). Most studies with integrated models rather analyze the macroeconomic costs of not exceeding a specific mitigation goal in the most cost-effective way (CEA, see SI section 1).

Since in this mode of operation mitigation scenarios do not account for avoided damages or co-benefits, the climate constraint to the respective optimization models leads to lower economic activity and hence a reduction of available consumption compared to baseline developments (Paltsev and Capros 2013). Depending on the modeling framework, these effects are measured in different metrics, such as the area under the marginal abatement curve, the aggregated and discounted increase in energy system costs, or aggregated and discounted GDP or consumption losses relative to GDP (see table S1). While many studies have analysed aggregate economic indicators for the mitigation costs, the analysis of delayed scenarios highlights that such cumulative metrics are not reflecting the full economic costs borne by societies: due to the discounting usually applied when calculating aggregated costs, sharp increases of costs in later decades (due to delayed climate policy scenarios) are not fully reflected in cumulative metrics. Metrics that measure transitional costs, such as the maximum transitional costs to be born within a decade, expressed as reduction of consumption growth, have been used to illustrate the economic challenges beyond the cumulative, discounted approach (Bertram *et al* 2015b, Kriegler *et al* 2013, Luderer *et al* 2013c) and can be calculated based on reported data from MESSAGE, GCAM and WITCH.

For the purpose of this letter, the indicator is defined as the maximum difference (in percentage change) in the consumption (C) growth rate (g) over a decade between mitigation and baseline scenarios in the same model – compared to a 1% change in the growth rate in the same period.

$$\max_{2010<t<2050}\left(g^{\text{Baseline}}(t) - g^{\text{Mitigation}}(t)\right)/1\%$$

where for each scenario

$$g(t) = \frac{C(t) - C(t-10)}{C(t-10)} \cdot 100\%$$

is the decadal rate of growth (in percentage change) for each scenario.

4.2.2 *Maximum decadal energy price growth*

Measuring the macroeconomic costs of mitigation for societies implicitly or explicitly takes into account inter-generational distributions by means of choosing a specific discount factor. But adjustment costs and intra-generational distribution issues are often neglected (Fleurbaey *et al* 2014, Fleurbaey and Zuber 2012). While direct analysis of the distributional impacts of climate policy is not possible with such global models with only coarse geographical scales and assumptions on homogeneity of economic agents (see SI section 2), some recent studies identified economic indicators that could be indirectly related to distributional issues. One example for such an indicator is the maximum growth of an energy price index to be born within a decade, calculated similarly to a consumer price index, due to climate policies (Bertram *et al* 2015b, Luderer *et al* 2013c). Although such an indicator is only an approximation for the actual increase of household expenditure for energy services (see SI section 3.1.3), it is an interesting alternative, given that energy services are not explicitly modelled in the majority of integrated models. Since the models that report secondary energy prices (MESSAGE and REMIND) include carbon price mark-ups, the indicator is set to increase for climate policy.

For the purpose of this letter, the indicator is defined as the maximum decadal increase in the Energy Price Index (*EPX*) in the given time period, where *EPX* is the weighted average of the price (*p*) of the secondary energy demand basket (*SE*) relative to the price of the same basket 10 years previously.

$$EPX(t) = \sum_i p_i(t) SE_i(t) \,/ \sum_i p_i(t-10) SE_i(t),$$

such that maximum decadal energy price growth (in percentage change) is

$$\max_{2010<t<2050} \frac{EPX_{\mathrm{Mitigation}}(t) - EPX_{\mathrm{Baseline}}(t)}{EPX_{\mathrm{Baseline}}(t)} \cdot 100\%$$

4.2.3 Idle coal capacity per year

Due to the high GHG emissions of the current, mainly fossil-based, energy system, stringent mitigation goals necessarily lead to a significant energy system transition (Bruckner *et al* 2014). Should the global community or individual countries ramp up climate policies, some existing and even newly built fossil capacities may turn out to be unprofitable since they are not able to recover their short-term costs, ending up as stranded investments (Bosetti *et al* 2009a) (see SI section 3.1.5).

Since integrated models project more carbon-intensive coal power plant build-up for the next decades in delayed mitigation pathways (assuming myopic investment behavior), these are the plants that would – under normal market conditions – still operate in 2050 but may have to be prematurely retired for suddenly high carbon prices after the period of delay (Bertram *et al* 2015a, Johnson *et al* 2015). This is approximated by the amount of 'idle coal capacity' in the models which depends on the carbon intensity reduction rates necessary to stay within the carbon budget which is more challenging the later emissions peak and the higher this peak level will be (Johnson *et al* 2015). Here, we build on the metric used by Bertram *et al* (2015a), who calculate the average load factor of the global coal capacity, albeit looking at the share lying idle in mitigation scenarios.

For the purpose of this letter, the indicator measures the percentage change in the share of coal power plant capacity – "Capacity|Electricity|Coal|w/o CCS" (*Capacity_Coal* in GW) – in 2050 that is not being used to generate electricity – "Secondary Energy|Electricity|Coal|w/o CCS" (*SE_Coal* in EJ/a) – i.e. is lying idle:

$$\frac{\left(1 - \frac{Capacity\_Coal^{\mathrm{Mitigation}}(2050)}{SE\_Coal^{\mathrm{Mitigation}}(2050)\cdot \mathrm{s/a}}\right) - \left(1 - \frac{Capacity\_Coal^{\mathrm{Baseline}}(2050)}{SE\_Coal^{\mathrm{Baseline}}(2050)\cdot \mathrm{s/a}}\right)}{\left(1 - \frac{Capacity\_Coal^{\mathrm{Baseline}}(2050)}{SE\_Coal^{\mathrm{Baseline}}(2050)\cdot 0.031536}\right)} \cdot 100\%$$

4.2.4 CO_2 captured and stored per year

In addition to other concerns (see SI section 3.1.9), one major uncertainty in the process chain of CCS are the hydrogeological characteristics and volumes of the geological reservoirs in which the CO_2 is supposed to be stored (Humpenöder *et al* 2014). Since the global storage potential of deep saline aquifers is large compared to alternative storage types (1000 up to 10000 Gt, see Benson *et al* 2005), the uncertainty about hydrogeological data leads to high ranges of estimates. The IEA qualifies the storage in depleted oil and gas fields for which reliable data already available as well as the usage of CO_2 for 'Enhance Oil Recovery (EOR)' as 'early opportunities' (IEA 2009). Since point sources of CO_2 do not necessarily arise in places with the largest storage sites, source-sink matching leads to lower storage potential estimates. If global CO_2 storage demand exceeds these estimates, more risky reservoir types have to be tapped.

Drawing on the regionally differentiated estimates of Hendriks *et al* (2004), the global CO_2 storage potential for depleted oil and gas fields stands at 250 Gt CO_2 (best estimate). Assuming an injection duration of 50 years (to avoid pressure build-up, see Szulczewski *et al* 2012), the storage potential per year amounts to 5 Gt. Although more storage volume is available from other reservoir types (deep saline aquifers, coalbed methane recovery), all values above 5 Gt are judged as more risky.

For the purpose of this letter, the indicator measures the percentage increase of CO_2 emissions stored – "Emissions|CO2|Carbon Capture and Storage" (*Emi_CCS*) – in geological storage facilities in 2050 relative to a reference value of 5000 Mt that can presumably be stored at low technical risks.

$$\frac{Emi_{\mathrm{CCS}^{\mathrm{Mitigation}}(2050)} - 5000\ \mathrm{Mt\ CO_2}}{5000\ \mathrm{Mt\ CO_2}} \cdot 100\%$$

4.2.5 Nuclear capacity expansion in Newcomer countries

Today, only thirty countries have nuclear energy but much of the development of nuclear power in low-carbon scenarios happens in regions where nuclear power has played a very small role. The question then becomes, does a spread of nuclear power increase the risk of proliferation and physical security concerns? The relationship between proliferation and civilian nuclear power programs is contentious to say the least. However, there is generally consensus that civilian nuclear power programs shorten the time it would take a country to develop the bomb (Sagan 2011). There's also empirical evidence that 'client' countries that have nuclear cooperation agreements with 'supplier' countries are more likely to develop nuclear weapons (Fuhrmann 2009). Since few 'Nuclear Newcomers' would be able to introduce nuclear power without significant international support (Jewell 2011), the growth of nuclear proliferation would increase with the spread of the technology to new countries.

To measure this risk, we developed an indicator for the (percentage) change in the capacity of nuclear power in countries which today do not currently have nuclear power. In the absence of country-by-country values, this is approximated as the sum of nuclear capacity – "Capacity|Electricity|Nuclear" (*Capacity_Nuc*) – in 2050 in regions (*r*) that largely do not have nuclear power (Asia, the Middle East and Africa and Latin America) less the sum of the projected nuclear capacity (i) in those countries which do (China, India and Brazil) and for which the AMPERE database supplies data.[5]

$$\frac{NewNuclear^{\text{Migitation}} - NewNuclear^{\text{Baseline}}}{NewNuclear^{\text{Baseline}}} \cdot 100\%,$$

where

$$NewNuclear = \sum_{r} Capacity\_Nuc(2050) - \sum_{i} Capacity\_Nuc(2050)$$

4.2.6 Biomass supply for energy per year

Biomass is a basic resource for food, fodder and fiber and is hence crucial to many peoples' well-being, particularly for those that have to rely on subsistence agriculture and on traditional biomass for cooking and heating. Since it is also a versatile form of RE, potentially being able to be converted to liquid and gaseous fuels, electricity and heat, it also plays an important role in integrated model projections of energy systems moving away from fossil-based fuels (Chum *et al* 2011, Smith *et al* 2014b). For many technological routes, this implies that bioenergy may compete with other biomass demand for arable land (Haberl *et al* 2014). Since land is a finite resource, this could lead to a range of effects for SD (see SI section 3.1.1).

Since there are many uncertainties involved in calculating the land use impact of bioenergy, including the (induced) yield changes through agricultural technology innovation and diffusion processes and the interactions with dietary patterns and non-climate policies (Creutzig *et al* 2012a, PBL 2012, Popp *et al* 2014, Rose *et al* 2012, Sathaye *et al* 2011, Smith *et al* 2014b, Wise *et al* 2009), we simply use the total amount of bioenergy as an imperfect but available indicator for this range of potential risks.

For the purpose of this letter, the indicator refers to the percentage change in the primary energy supply of biomass – "Primary Energy|Biomass" (*Bioenergy*) – in 2050 relative to the baseline scenario.

$$\frac{Bioenergy^{\text{Mitigation}}(2050) - Bioenergy^{\text{Baseline}}(2050)}{Bioenergy^{\text{Baseline}}(2050)} \cdot 100\%$$

4.2.7 Maximum decadal PV and wind capacity upscaling

Modern electrical power systems widely differ in terms of their development and reliability across countries. But the balancing of electricity supply and demand requires complex operational planning from the management of instantaneous changes in demand to the longer-term investment decisions in generation capacity and transmission grids. Because the generators, interconnectors and loads are designed to operate within certain frequency limits, large amounts of only partially dispatchable and predictable power capacity are potentially a threat to the security and reliability of the system. This entails the need to build new grid infrastructure (e.g. grid reinforcements and new lines) both inside the region as well as interconnection to neighbouring regions. But because the construction of networks involves long lead times, "… major investments will be needed and will need to be

[5] Although South Korea (21.6GW) and South Africa (1.8GW) already have nuclear capacity (whose lifetime ends, however, before 2050), the AMPERE database does not report country-specific data in these cases. This likely implies a slight overestimation of the nuclear newcomers capacity – in baseline and mitigation scenarios.

undertaken in such a way, and far enough in advance, so as to not jeopardize the reliability and security of electricity supply (Sims *et al* 2011, p 627)."

With timing conflicts (PV and wind plants can be constructed in less than 2 years, while planning, permitting and constructing a transmission line takes 5 to 10 years) and cost recovery uncertainties, very fast upscaling of PV and wind power plants is a risk – both technically and economically (Sims *et al* 2011). Possible other solutions (such as curtailment, provision of ancillary services, demand-side measures and additional reserve capacity and storage facilities) may have to be relied on for higher penetration rates but also requires additional time and/or investments (Hirth 2013, Hirth and Ueckerdt 2013, Holttinen *et al* 2011, Söder *et al* 2007, Ueckerdt *et al* 2013). Because the majority of integrated models only report the various variables in 10-year time steps, we have to rely on decadal values for upscaling that we use as a mitigation risk indicator reflecting both technical and economic risks.

For the purpose of this letter the indicator refers to the maximum decadal increase (in percentage change) in the combined capacity of PV and wind power – "Capacity|Electricity|Solar|PV" (*Capacity_PV*) and "Capacity|Electricity|Wind" (*Capacity_Wind*) – between 2010 and 2050 relative to the maximum decadal increase in capacity in baseline scenarios.

$$\frac{CapacityUpscaling^{\text{Migitation}}(t) - CapacityUpscaling^{\text{Baseline}}(t)}{CapacityUpscaling^{\text{Baseline}}(\mathrm{t})} \cdot 100\%,$$

where

$$CapacityUpscaling = \max_{2010<t<2050} Capacity\_PV(t) + Capacity\_Wind(t)$$

4.2.8 Cumulative CO_2 emissions

As described in SI section 1, the emission pathways in integrated model mitigation scenarios are designed to meet different atmospheric CO_2eq concentrations or carbon budgets by 2100. They are, however, given the flexibility to overshoot the constraint over the course of the century. Otherwise, many models would not find a solution for mitigation scenarios with very low concentration targets. This implies that CO_2 emission trajectories and concentrations can differ substantially across alternative 2°C pathways – mainly depending on the deployment levels of negative emission technologies in the second half of the century (Clarke *et al* 2014, Fuss *et al* 2014). As described in SI section 3.1.10, this can have very different implications for the marine environment, because past CO_2 emissions can leave a substantial legacy in the marine environment due to delayed responses in the ocean interior and irreversibility of some of the impacts of ocean acidification, such as calcification (Boucher *et al* 2012, Zickfeld *et al* 2012). We hence look at differences in cumulative CO_2 emissions by 2050 in alternative 2°C pathways to approximate the changes is risks due to ocean acidification and its implication for marine ecosystems.

For the purpose of this letter, the indicator refers to the percentage change in cumulative CO_2 emissions – "Emissions|CO2" (*Emi_CO2*) – from 2020-2050.

$$\frac{Emi\_CO2^{\text{Mitigation}} - Emi\_CO2^{\text{Baseline}}}{Emi\_CO2^{\text{Baseline}}} \cdot 100\%$$

Cumulative values are calculated by multiplying the value in each timestep (t) by half the difference between that timestep's year (Y) and the previous timestep's year plus half the difference between its year and the next timestep's year, for all timesteps included in the period under consideration.

4.2.9 Cumulative SO_2 and BC emissions

The emissions arising from the combustion of fossil fuels, such as soot (black carbon, BC), sulfur dioxide (SO_2), nitrogen oxides (NOx) and mercury (Hg), cause significant and widespread human health impacts as well as ecological impacts as described in SI section 3.1.2. Although the negative environmental and health impacts primarily arise from the (regionally very different) concentration of these pollutants, the scenario databases merely report the amount of global emissions that serve here as indicator. There are, however, individual studies that establish a clear link between emissions, concentrations and the negative impacts of the pollutants in question (Rao *et al* 2013, Shindell *et al* 2012, Smith and Mizrahi 2013).

For the purpose of this letter, the indicator for cumulative BC Emissions (2020-2050) refers to the percentage change in the cumulative value of BC emissions – "Emissions|BC" (*Emi_BC*) – from 2020 to 2050 relative to the baseline scenario.

$$\frac{Emi\_BC^{\mathrm{Mitigation}} - Emi\_BC^{\mathrm{Baseline}}}{Emi\_BC^{\mathrm{Baseline}}} \cdot 100\%$$

For the purpose of this letter, the indicator for cumulative SO_2 Emissions (2020-2050) refers to the percentage change in the cumulative value of sulfur emissions – "Emissions|Sulfur" (*Emi_SO2*) – from 2020 to 2050 relative to the baseline scenario.

$$\frac{Emi\_SO2^{\mathrm{Mitigation}} - \mathrm{Emi}\_SO2^{\mathrm{Baseline}}}{Emi\_SO2^{\mathrm{Baseline}}} \cdot 100\%$$

4.2.10 Cumulative global oil trade

For oil trade, we measure interregional oil trade as an indicator for the concerns around the sovereignty perspective that sees the origin of risks in deliberate actions of foreign actors (Jewell *et al* 2014). While this indicator does capture lower risks from decreasing oil imports, it also measures lost oil export revenues for oil exporters, which is most likely a loss rather than a benefit for major oil exporting countries which would lose oil export revenues from a fall of oil trade (Clarke *et al* 2014).

With increasing ambition of mitigation, however, global oil trade is projected to significantly decrease. One important aspect is that development pathways characterized by lower energy intensity (EI) are often likely to rely more heavily on oil than mitigation scenarios with conventional EI assumptions (see figure S5) because the mitigation options in the transport sectors are among those with the highest costs (Kriegler *et al* 2014b). Theoretically, the mitigation costs saved from lower EI could be used to lower the energy security risks around the reliance of the transport sector on oil.

For the purpose of this letter, the indicator refers to the percentage change in global oil imports, i.e. the sum of positive "Trade|Primary Energy|Oil|Volume" in each region *r* between 2020 and 2050 (*Trade_Oil*) relative to the baseline scenario.

$$\frac{\sum_r Trade\_Oil_r^{\text{Mitigation}} - \sum_r Trade\_Oil_r^{\text{Baseline}}}{\sum_r Trade\_Oil_r^{\text{Baseline}}} \cdot 100\%$$

4.2.11 Cumulative oil extraction

For the robustness perspective related to oil security, we measure the cumulative extraction of oil resources as a relevant indicator for judging scarcity concerns (Jewell *et al* 2014). While the 'peak-oil' theory is still debated, even the perception of resource scarcity can lead to price volatility (McCollum *et al* 2013). Although global conventional oil reserves are limited, oil demand projections often exceed these already by 2050 in baseline scenarios (Rogner *et al* 2012). An alternative to conventional oil reserves would be to draw on so-called unconventional oil reserves. This alternative is, however, problematic, as there is considerable evidence that unconventional oil production involves bigger environmental and health risks as well as an increased carbon intensity of production, relative to conventional oil production (Bruckner *et al* 2014, Rogner *et al* 2012). For instance, Canada's oil sands production appears to generate three times as many GHG emissions as its conventional oil production. Moreover, it is plausible that part of the water used in oil sands production pollutes the ground water. There is also evidence of it altering ecosystems (Engemann and Owyang 2010, Woynillowicz *et al* 2005).

Analogously, the production of oil shale has also been found to emit more GHGs than conventional oil production, decrease water quality, and permanently change ecosystems (Bartis *et al* 2005, Engemann and Owyang 2010). As a final example, Rogner *et al* (2012, p. 437) note that "severe soil and water contamination by chlorinated hydrocarbons and heavy metals" is likely to result from the processing of raw unconventional oil into sellable oil.

For the purpose of this letter, the indicator refers to the percentage change in the cumulative extraction of crude oil – "Resource|Cumulative Extraction|Oil" (*Oil*) – between 2020 and 2050 relative to the baseline scenario.

$$\frac{Oil^{\text{Mitigation}} - Oil^{\text{Baseline}}}{Oil^{\text{Baseline}}} \cdot 100\%$$

4.2.12 Fuel diversity of transport sector

For the resilience perspective, we measure the fuel diversity of the transport sector which currently is very low in most countries of the world due to high reliance on oil (Cherp *et al* 2012). For countries that are net importers of oil, the exposure to volatile and unpredictable oil prices affects the terms of trade and their economic stability (Sathaye *et al* 2011). Electrification of the transport sector and switching to biofuels would decrease the oil dependency by diversifying the energy supply, thus increasing resilience (Jewell *et al* 2014). Although mitigation scenarios often project less oil demand by 2050 relative to baseline developments, cost-effective technological options in the transport sector to substitute oil are still limited (Sims *et al* 2014). Global roll-out of alternative propulsion technology, particularly in the individual mobility sector, is likely to require clear price signals in many countries (either through global cooperation on carbon pricing or transport sector innovation) to spread the enormous investment costs in R&D, early deployment and diffusion (Bosetti *et al* 2011).

For the purpose of this letter, the indicator refers to the percentage change in the Shannon Wiener Diversity Index (SWDI) – multiplied by -1 to measure transport sector oil reliance, a SD risk, rather than fuel diversity of the transport sector, a policy objective – of the five most widely used final energy carriers in the transport sector – oil ('Final Energy|Transportation|Liquids|Oil'), biofuels ('Final Energy|Transportation|Liquids|Biomass'), gases ('Final Energy|Transportation|Gases'), electricity ('Final Energy|Transportation|Electricity'), and hydrogen ('Final Energy|Transportation|Hydrogen'). The SWDI is the sum of the share of each final energy carrier (*f*) in total final transport energy ('Final Energy|Transportation') (*t*) multiplied by its natural logarithm.

$$\frac{\sum_f(\frac{f}{t} \cdot \ln(\frac{f}{t}))^{\text{Mitigation}} - \sum_f(\frac{f}{t} \cdot \ln(\frac{f}{t}))^{\text{Baseline}}}{\sum_f(\frac{f}{t} \cdot \ln(\frac{f}{t}))^{\text{Baseline}}} \cdot 100\%$$

5 AMPERE model inter-comparison project

AMPERE is an EU-funded international effort that stands for ‘Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates’. This inter-comparison project of integrated models focused on the mitigation challenge of delayed and fragmented climate policy. AMPERE compares results from a wide range of internationally recognized energy-economy-climate models with different functional structures, parametric assumptions, and sectoral coverage (see table S1). The model diversity allowed identifying model uncertainty (i.e., where model results differed widely) and robust insights (i.e., where model results were similar).

AMPERE covered several key aspects not assessed in previous inter-comparison projects:

- Impact of short-term climate policies on the achievability of long-term mitigation goals;
- Role of individual technologies within the mitigation technology portfolio;
- Harmonization of key socioeconomic drivers (GDP, population and energy demand growth);
- Economic effects and climate benefits of early unilateral followed by delayed global action;
- Costs and benefits of alternative European Union climate policy choices;
- Diagnosing model behavior and assessing model validity to better understand differences.

The first two aspects are particularly important for this letter’s analysis which is why the respective scenario specifications are described in more detail in table S3. The third point is also of importance for this analysis (see discussion) since harmonized key socioeconomic drivers allow a better mapping of the changes in the model variables to climate policy signals across models. The main finding of AMPERE is that any emissions resulting from low-ambitious short-term climate policies (until 2030) would need to be compensated over a relatively short timeframe (2030-2050) to stay within the limited carbon budget associated with restricting warming to 2°C (see figure S3).

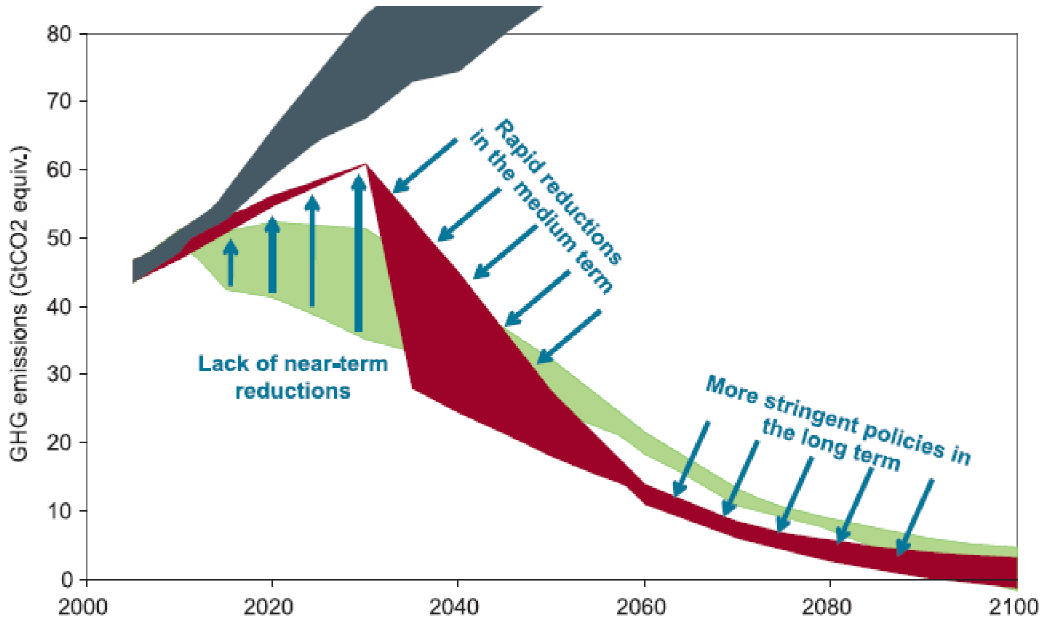

Figure S3. GHG emission pathways of AMPERE models necessary to stay within the carbon budget consistent with the 2°C target. The optimal pathway with immediate mitigation is shown in green while the red emission pathway represents delayed 2°C pathways. The grey emission pathway denotes baseline development without climate policy. Source: Kriegler *et al* (2014a).

Mitigation scenarios with low-ambitious short-term climate policies ("HST") would require quadrupling the low-carbon energy share and global CO_2 emission cuts of 6-8% per year in the two decades between 2030 and 2050. This means that almost half the global energy supply infrastructure would require replacement over a narrow two decade period. In optimal immediate climate policy scenarios ("OPT"), the energy system transition between 2030 and 2050 required to limit warming to 2°C would still be highly challenging, requiring a doubling of the low-carbon energy share and carbon intensity reductions of 3-4% per year (see figure S4).

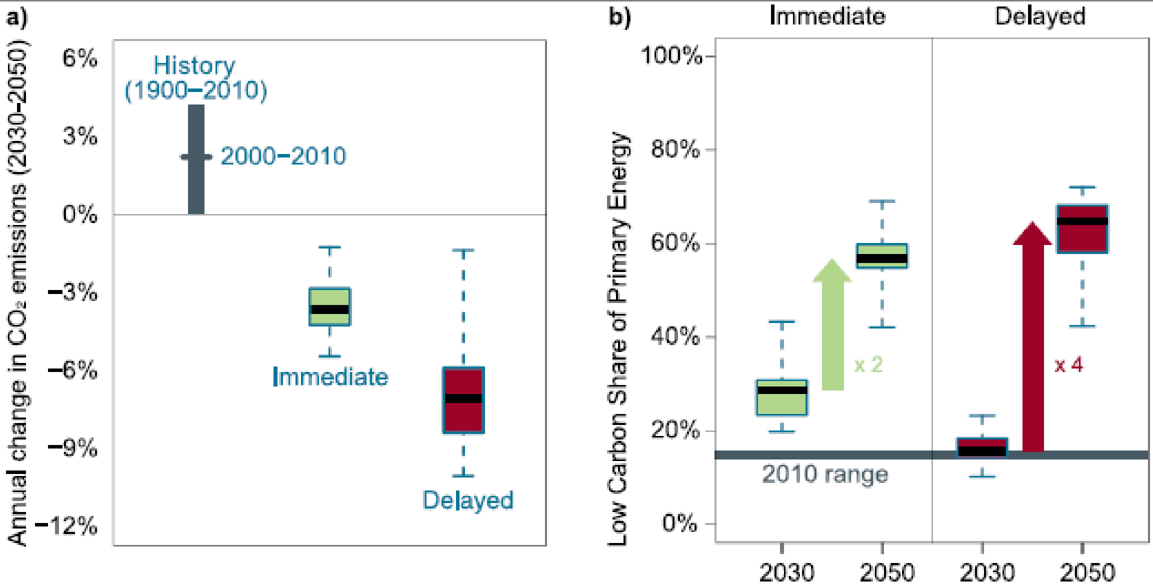

Figure S4. Comparison of delayed and immediate mitigation pathways consistent with 2°C. Panel (a) illustrates the required carbon intensity reduction rates and panel (b) the required upscaling of low-carbon energy supply. Historical annual carbon intensity change rates from 1900 to 2010 (sustained over 20-year periods) are shown in grey in panel (a). Boxplots indicate median, interquartile and full ranges of model results. Source: Kriegler *et al* (2014a).

The AMPERE models project a global mean warming of 3.5 – 5.9°C above pre-industrial levels by 2100 for the baseline scenarios, depending on the uncertainty in emissions and climate parameters (table S2). By contrast, all mitigation scenarios that are analyzed in this letter are scenarios designed to stay within the cumulative emission budget of 1500 $GtCO_2$ (2000–2100) – which largely corresponds to the mitigation scenarios with 450 ppm CO_2-equivalent concentrations at the end of the century (Clarke *et al* 2014, Riahi *et al* 2015, Schaeffer *et al* 2015). For median assumptions, this implies a 42-47% probability of not exceeding the 2°C target for all 450-FullTech scenarios which corresponds to maximum temperature changes of 2.5°C (see table S3).

Table S2. GHG emissions, atmospheric concentrations, and temperature consequences in the "FullTech" scenarios. Numbers correspond to the median and the full range across the scenarios. Note that for the climate simulations, emissions were harmonized to the same base year using inventories from Granier *et al* (2011) and Lamarque *et al* (2010) (adapted from Riahi *et al* 2015).

	CO_2 Emission (2030) $GtCO_2$	CO_2eq Emissions (2030) $GtCO_2$e	Cumulative CO_2 emissions (2000-2100) $GtCO_2$	CO_2eq concentrations (2100) ppm	Temperature change (max) °C	Probability of exceeding 2°C (max) %
Baseline	53 (50-67)	71 (68-83)	6,268 (5,670-8,755)	1,143 (1,023-1,338)	4.6 (3.5-5.9)	100 (100-100)
450 optimal	31 (24-45)	46 (35-60)	1,330 (1,242-1,350)	485 (453-522)	1.9 (1.5-2.4)	42 (26-84)
450 LST	39 (37-42)	53 (53-53)	1,335 (1,263-1,379)	488 (455-524)	2.0 (1.5-2.5)	45 (28-84)
450 HST	46 (44-49)	61 (60-61)	1,344 (1,274-1,382)	484 (452-520)	2.0 (1.6-2.5)	47 (28-84)

Table S3. Mitigation technology choices and short-term climate policy stringencies assumed in the AMPERE scenarios (adapted from Riahi *et al* 2015).

Short-term targets (2030)	Description	Scenario name
Low short-term target	Global emissions follow a high ambition pledge pathway reaching 53 $GtCO_2$eq by 2030. Thereafter ambitions are adjusted to meet the long-term target (450 CO_2eq)	"LST"
High short-term target	Global emissions follow a low ambition pledge pathway reaching 61 $GtCO_2$eq by 2030. Thereafter ambitions are adjusted to meet the long-term target (450 CO_2eq)	"HST"
Optimal policy	Global emissions follow an optimal pathway assuming immediate introduction of climate policies to meet the long-term target (450 ppm CO_2eq). No explicit short-term target for 2030 is assumed.	"OPT"
Technology cases	**Description**	**Scenario name**
Full technology	The full portfolio of technologies is available and may scale up successfully to meet the respective climate targets	"FullTech"
Low Demand and Energy Intensity	A combination of stringent efficiency measures and behavioural changes radically limits energy demand, leading to a doubling of the rate energy intensity improvements compared to the past. The full portfolio of technologies is available on the supply side.	"LowEI"
No new nuclear	No new investments into nuclear power after 2020; existing plants are fully phased out over their life time.	"NucOff"
No CCS	The technology to capture and geologically store carbon dioxide (CCS) never becomes available. This impacts both the potential to implement lower emission options with fossil fuels and the possibility to generate "negative emissions" when combined with bioenergy.	"NoCCS"
Limited Solar and Wind	Limited contribution of solar and wind to 20% of total power generation, reflecting potential implementation barriers of variable renewable energy at high penetration rates	"LimSW"
Limited Biomass	Limited potential for biomass (maximum of 100 EJ/yr), exploring strategies that would avoid large-scale expansion of bioenergy and thus avoid potential competition over land for food and fibre	"LimBio"

6 Supplementary figures

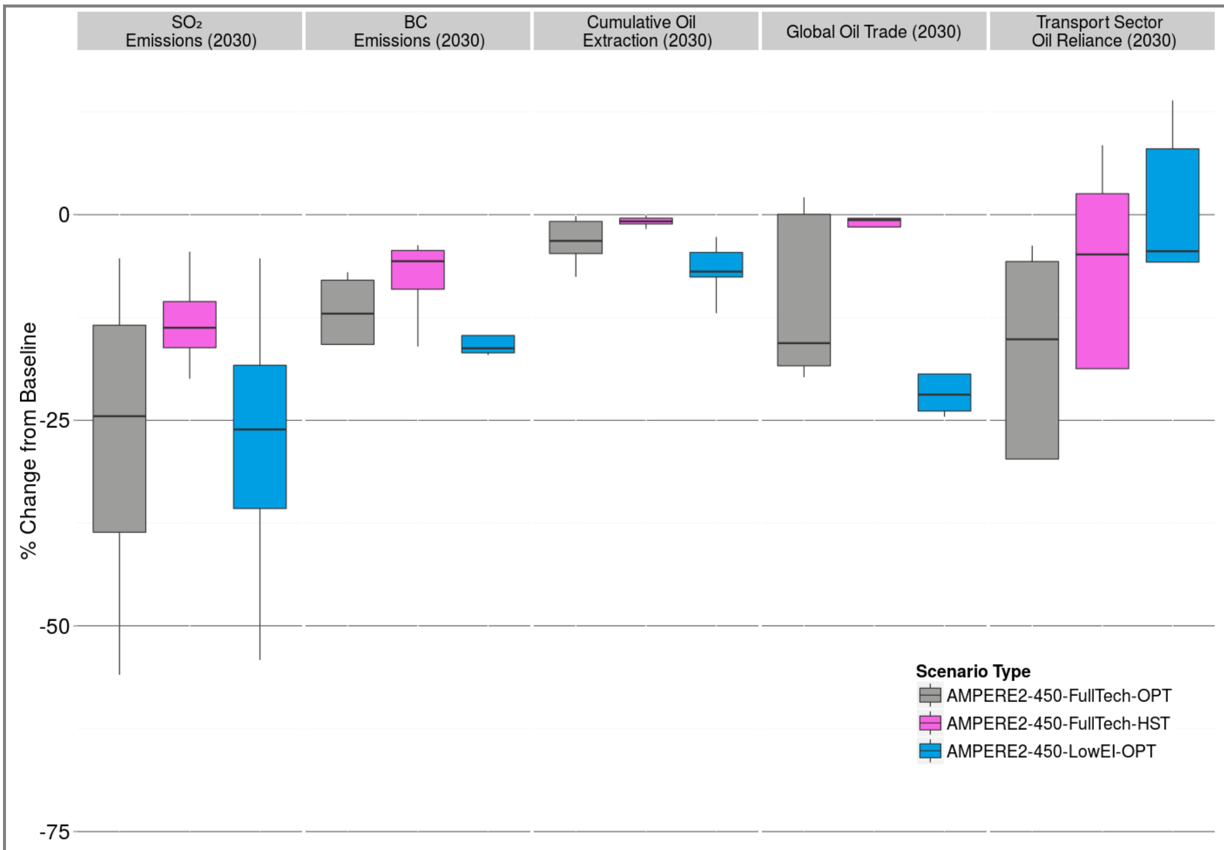

Figure S5. Percentage changes in indicators for co-benefits for air quality, oil security and fuel diversity in the transport sector in alternative 2°C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to baseline scenarios in 2030, comparing immediate mitigation scenarios (grey) with delayed mitigation scenarios (pink) and immediate mitigation scenarios with lower energy demand growth (blue). The thick coloured lines show median results, coloured ranges show interquartile ranges and whiskers show the minimum and maximum results.

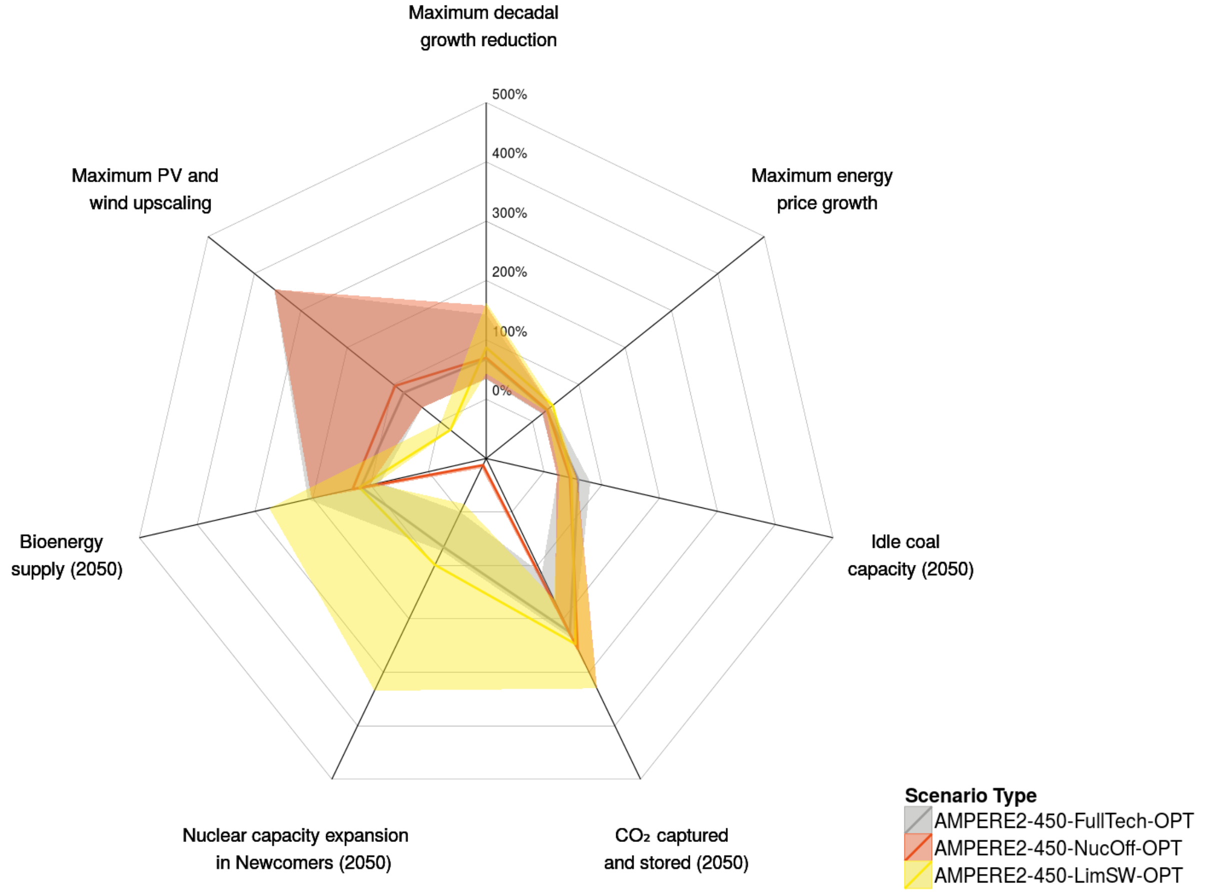

Figure S6. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for five integrated models (GCAM, IMAGE, MESSAGE, POLES, REMIND) relative to baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with mitigation scenarios assuming no new nuclear capacity (red) or limited potential for solar and wind energy (yellow). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

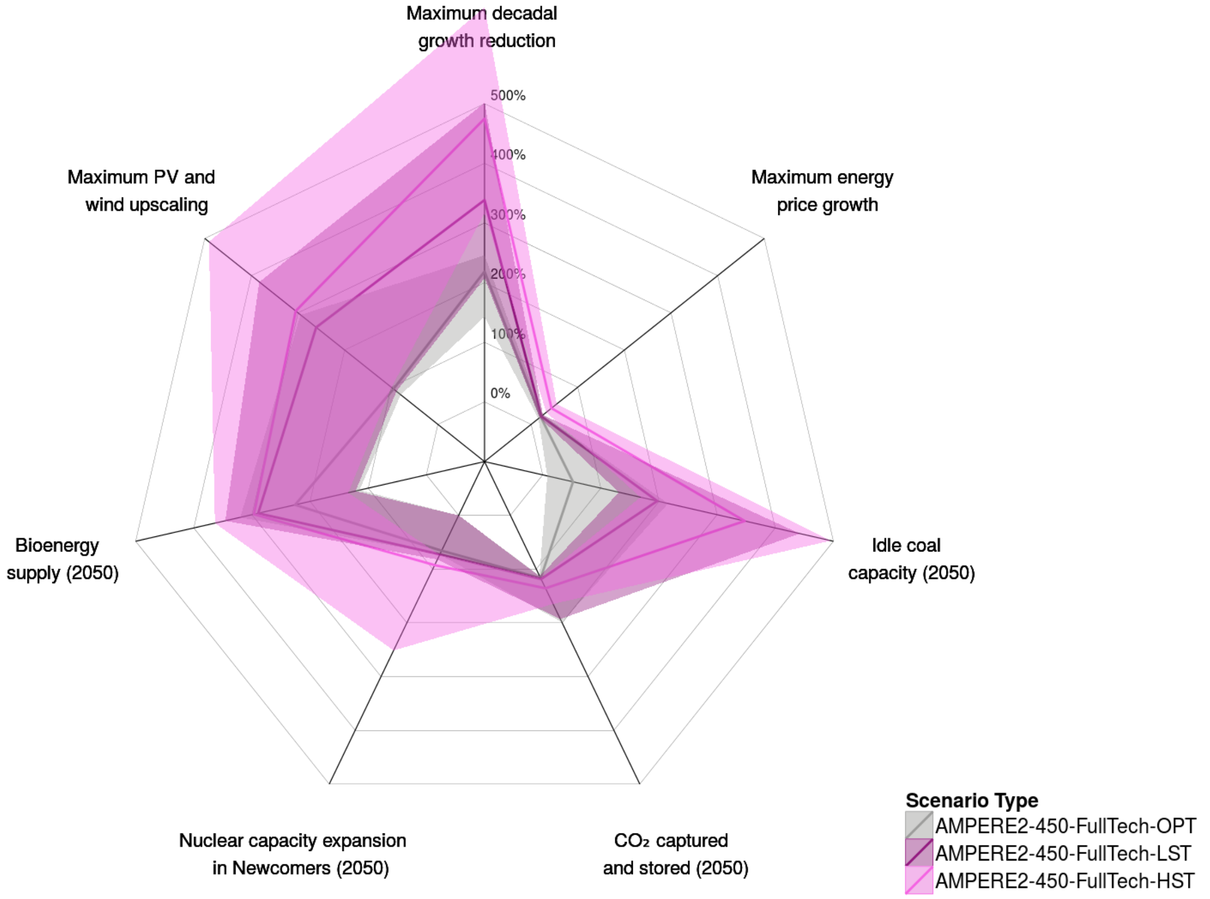

Figure S7. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for six integrated models (DNE21+, GCAM, MESSAGE, POLES, REMIND, WITCH) relative to baseline scenarios, comparing immediate mitigation scenarios (grey) with delayed mitigation scenarios with high short-term targets (pink) or low short-term targets (purple). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

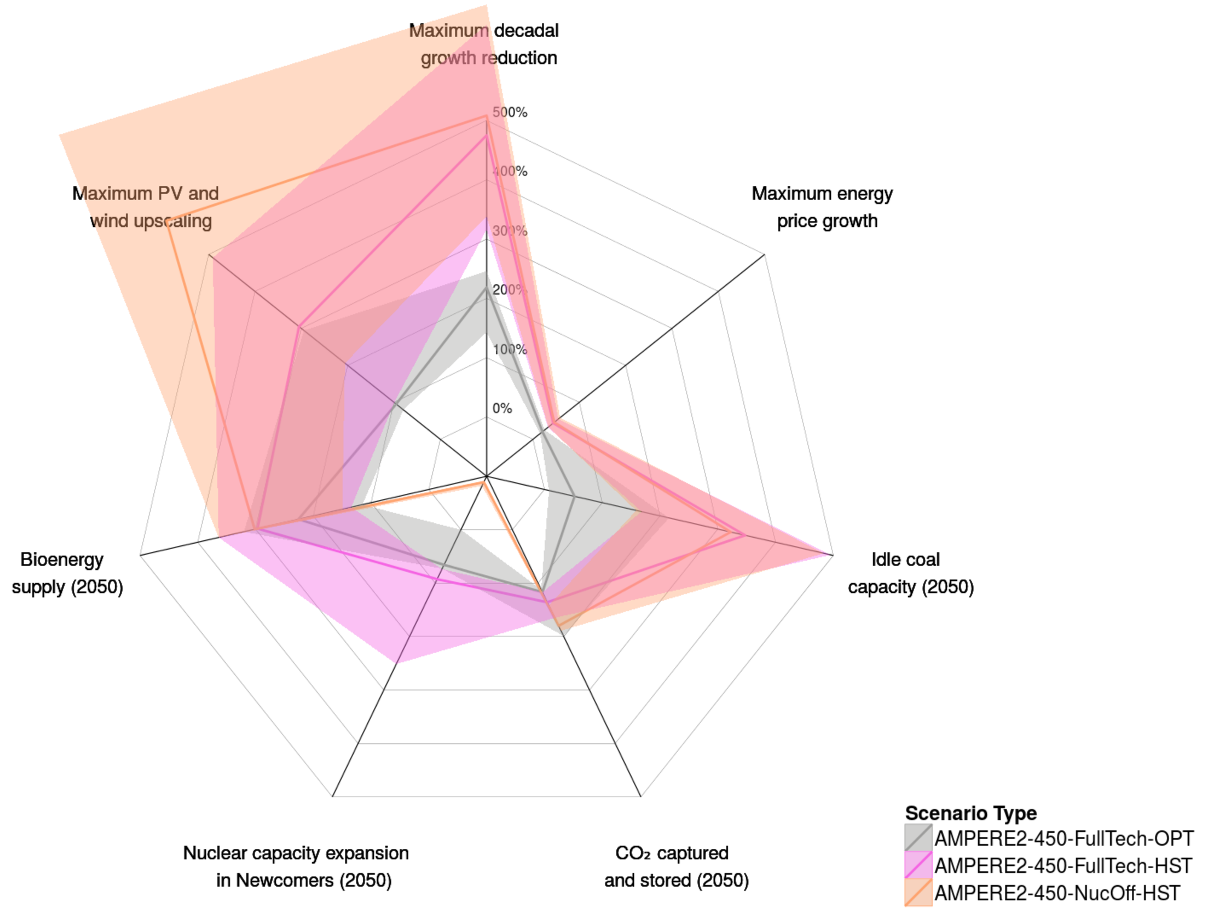

Figure S8. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for six integrated models (DNE21+, GCAM, MESSAGE, POLES, REMIND, WITCH) relative to reference values or values from baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with delayed mitigation scenarios assuming full availability of mitigation technologies (pink) or no new nuclear capacity (red). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

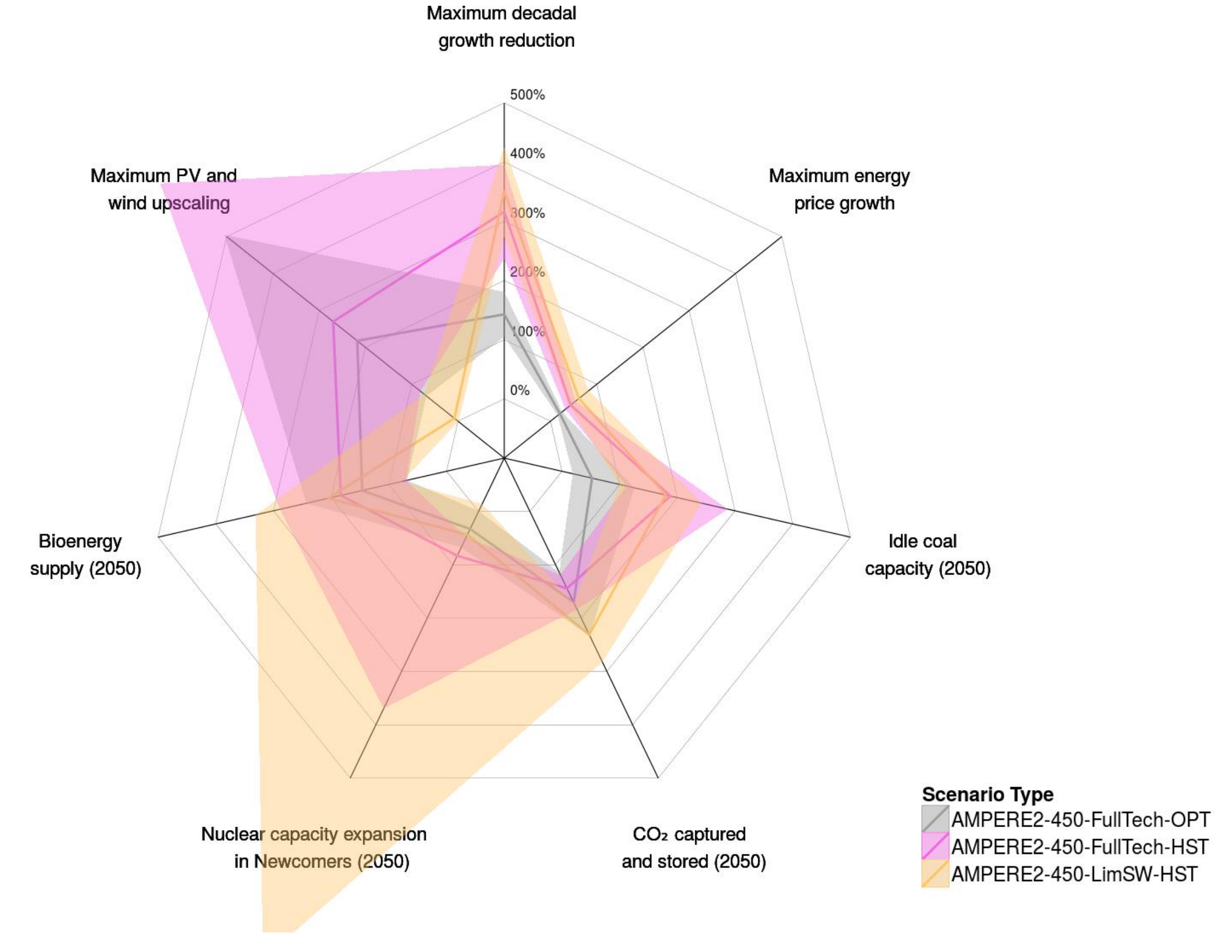

Figure S9. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to reference values or values from baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with delayed mitigation scenarios assuming full availability of mitigation technologies (pink) or limited potential for solar and wind energy (warm yellow). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

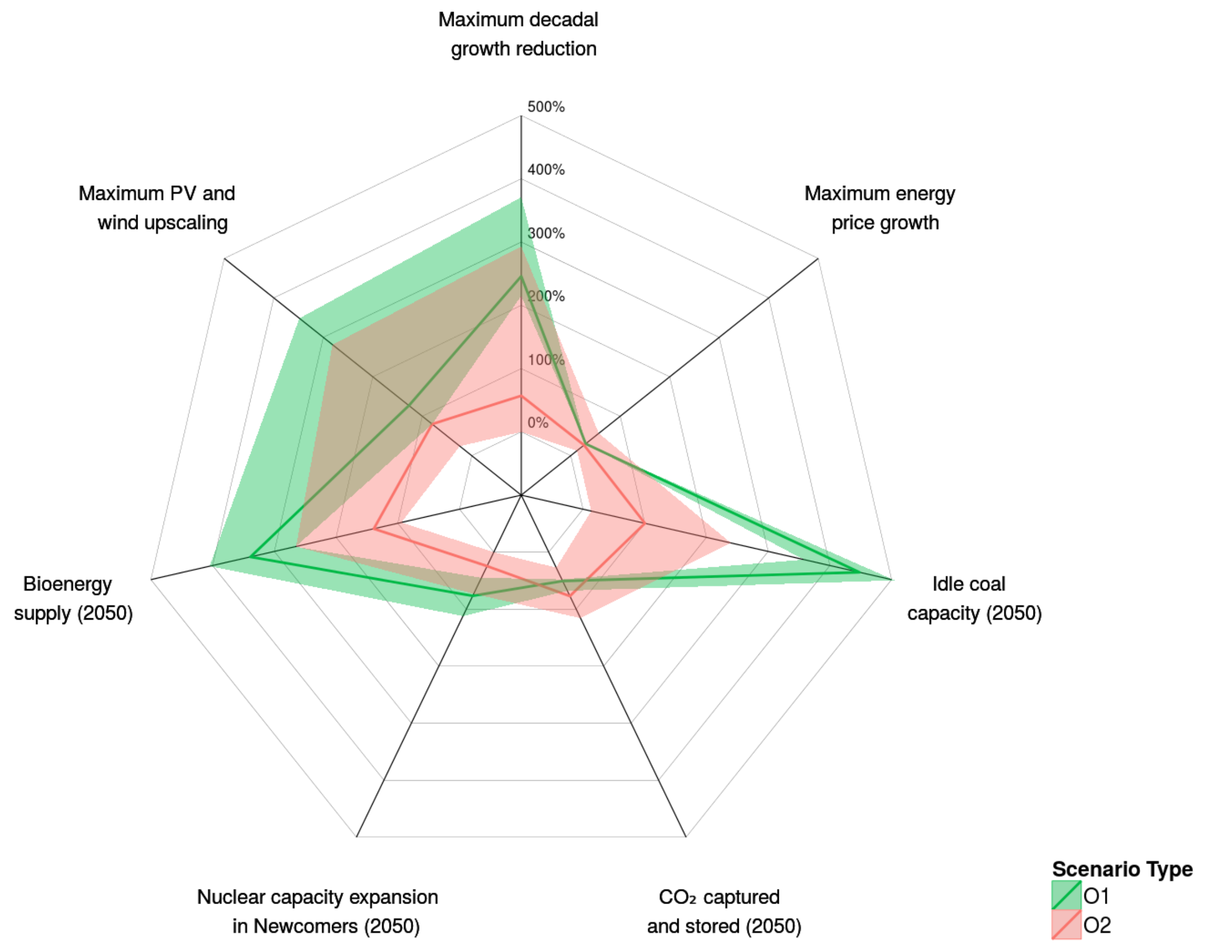

Figure S10. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for the year 2050 and the preceding decades for seven integrated models (DNE21+, GCAM, IMAGE, MESSAGE, POLES, REMIND, WITCH) relative baseline scenarios, comparing mitigation scenarios assuming full availability of mitigation technologies with low overshoot 'O1' (< 0.4 W/m^2) and high (> 0.4 W/m^2) overshoot 'O2' (see Clarke *et al* 2014 for details). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

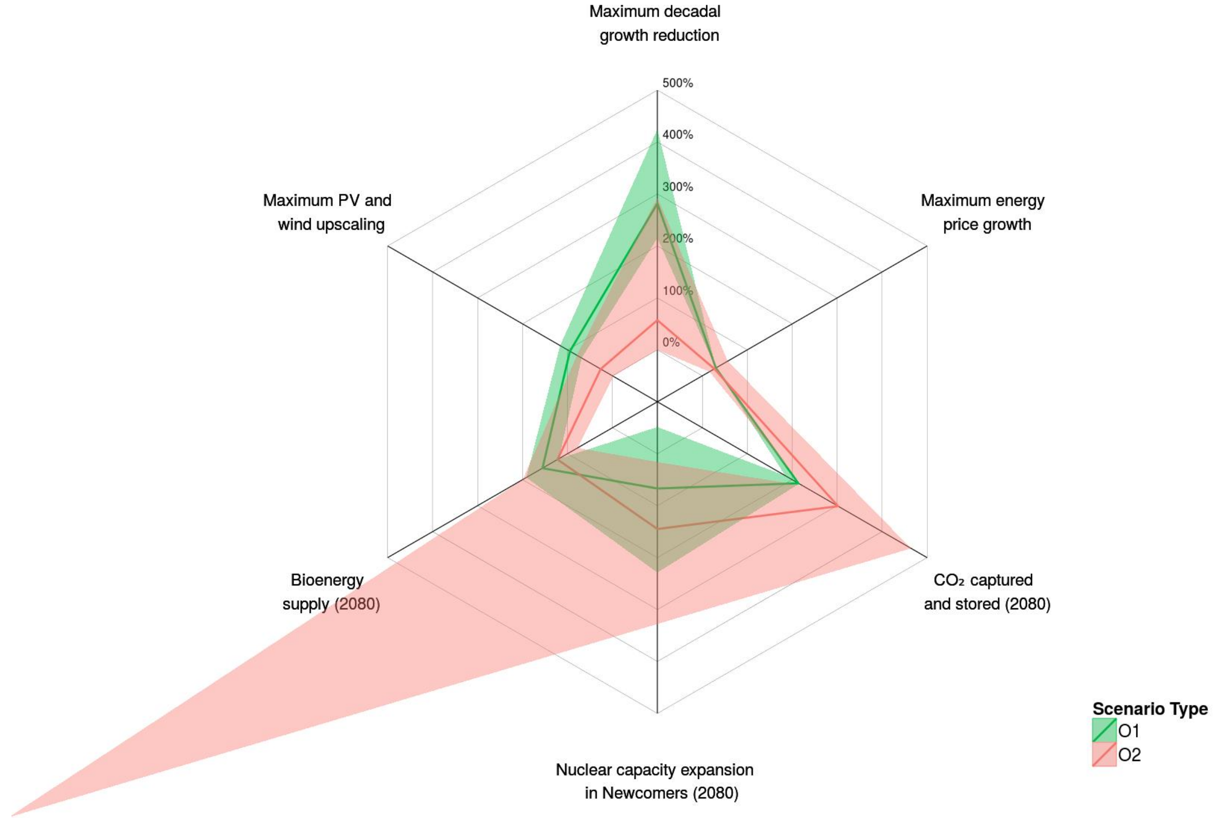

Figure S11. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for the year 2080 and the preceding decades for seven integrated models (DNE21+, GCAM, IMAGE, MESSAGE, POLES, REMIND, WITCH) relative to baseline scenarios, comparing mitigation scenarios assuming full availability of mitigation technologies with low overshoot 'O1' (< 0.4 W/m^2) and high (> 0.4 W/m^2) overshoot 'O2' (see Clarke *et al* 2014 for details). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

Table S4. Data underlying Figure 5. Percentage changes in median values of indicators for SD risk dimensions in different constrained 2°C pathways relative to optimal pathways (assuming immediate mitigation with full availability of mitigation technologies and conventional energy demand growth).

Mitigation scenario	Indicator	Median value of indicator...	Median value of 'optimal' 2°C scenario...	Percentage change [%]	Year(s)		DNE21 V.12	GCAM 3.0	MESSAGE V.4	POLES AMPERE	REMIND 1.5	WITCH_ AMPERE
		...of the respective models										
AMPERE2-450-FullTech-OPT	Cumulative CO_2 Emissions [Gt]	812896,90	812896,90	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumulative CO_2 Emissions [Gt]	813594,96	812896,90	**0,1**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumulative CO_2 Emissions [Gt]	805455,62	873256,50	**-1,6**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumulative CO_2 Emissions [Gt]	676945,25	873256,50	**-24,2**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumulative CO_2 Emissions [Gt]	721414,77	873256,50	**-27,9**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative CO_2 Emissions [Gt]	821073,44	812896,90	**0,2**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumulative CO_2 Emissions [Gt]	843678,04	812896,90	**7,6**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumulative CO_2 Emissions [Gt]	842362,81	812896,90	**7,5**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumulative CO_2 Emissions [Gt]	901729,82	873256,50	**3,4**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Cumulative CO_2 Emissions [Gt]	781099,87	873256,50	**-6,7**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumulative CO_2 Emissions [Gt]	812376,62	1026093,61	**-17,2**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Cumulative CO_2 Emissions [Gt]	864305,32	812896,90	**11,7**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Cumulative SO_2 Emissions [Gt]	1748,35	1748,35	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumulative SO_2 Emissions [Gt]	1738,58	1748,35	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumulative SO_2 Emissions [Gt]	1509,10	1560,63	**-3,3**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumulative SO_2 Emissions [Gt]	1324,99	1560,63	**-16,1**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumulative SO_2 Emissions [Gt]	1248,98	1748,35	**-22,2**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative SO_2 Emissions [Gt]	1698,26	1748,35	**1,4**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumulative SO_2 Emissions [Gt]	1724,12	1748,35	**2,4**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumulative SO_2 Emissions [Gt]	1727,50	1748,35	**2,3**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumulative SO_2 Emissions [Gt]	1594,31	1560,63	**2,2**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Cumulative SO_2 Emissions [Gt]	1495,05	1560,63	**-2,7**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumulative SO_2 Emissions [Gt]	1782,04	2021,98	**-12,5**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Cumulative SO_2 Emissions [Gt]	1753,20	1748,35	**7,3**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Cumulative BC Emissions [Gt]	186,11	186,11	**0,0**	2020-50		x	x	x		x	
AMPERE2-450-NucOff-OPT	Cumulative BC Emissions [Gt]	186,95	186,11	**0,0**	2020-50		x	x	x		x	
AMPERE2-450-LimSW-OPT	Cumulative BC Emissions [Gt]	172,44	176,57	**-2,3**	2020-50			x	x		x	
AMPERE2-450-LimBio-OPT	Cumulative BC Emissions [Gt]	167,65	176,57	**-8,9**	2020-50			x	x		x	
AMPERE2-450-NoCCS-OPT	Cumulative BC Emissions [Gt]	172,89	186,11	**-7,1**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative BC Emissions [Gt]	166,20	168,89	**-1,6**	2020-50		x	x	x		x	
AMPERE2-450-FullTech-LST	Cumulative BC Emissions [Gt]	178,17	186,11	**-1,6**	2020-50		x	x	x		x	
AMPERE2-450-NucOff-LST	Cumulative BC Emissions [Gt]	178,99	186,11	**-1,1**	2020-50		x	x	x		x	
AMPERE2-450-LimSW-LST	Cumulative BC Emissions [Gt]	161,61	176,57	**-1,7**	2020-50			x	x		x	
AMPERE2-450-LimBio-LST	Cumulative BC Emissions [Gt]	159,42	176,57	**-9,7**	2020-50			x	x		x	
AMPERE2-450-NoCCS-LST	Cumulative BC Emissions [Gt]	203,10	212,57	**-4,7**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Cumulative BC Emissions [Gt]	166,19	186,11	**-5,4**	2020-50		x	x	x		x	
AMPERE2-450-FullTech-OPT	Cumlative global oil trade [EJ]	3338,07	3338,07	**0,0**	2020-50			x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumlative global oil trade [EJ]	3369,41	3338,07	**-0,2**	2020-50			x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumlative global oil trade [EJ]	3294,56	3307,93	**-0,4**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumlative global oil trade [EJ]	3094,82	3307,93	**-8,1**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumlative global oil trade [EJ]	2881,66	3338,07	**-13,7**	2020-50			x	x		x	
AMPERE2-450-LowEI-OPT	Cumlative global oil trade [EJ]	3014,26	3338,07	**-8,0**	2020-50			x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumlative global oil trade [EJ]	3378,56	3338,07	**-0,5**	2020-50			x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumlative global oil trade [EJ]	3375,27	3338,07	**1,1**	2020-50			x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumlative global oil trade [EJ]	3307,45	3307,93	**-0,6**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Cumlative global oil trade [EJ]	3082,99	3307,93	**-6,8**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumlative global oil trade [EJ]	2875,70	3338,07	**-13,9**	2020-50			x				
AMPERE2-450-LowEI-LST	Cumlative global oil trade [EJ]	3087,27	3338,07	**-5,8**	2020-50			x	x	x	x	x
AMPERE2-450-FullTech-OPT	Cumulative oil extraction [EJ]	6149,59	6149,59	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumulative oil extraction [EJ]	6144,59	6149,59	**-0,4**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumulative oil extraction [EJ]	6039,16	6149,59	**-1,7**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumulative oil extraction [EJ]	5142,31	6149,59	**-10,5**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumulative oil extraction [EJ]	5362,68	6451,85	**-17,1**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative oil extraction [EJ]	5729,45	6149,59	**-7,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumulative oil extraction [EJ]	6016,11	6149,59	**0,6**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumulative oil extraction [EJ]	6020,79	6149,59	**0,9**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumulative oil extraction [EJ]	6082,86	6149,59	**-1,1**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Cumulative oil extraction [EJ]	5134,03	6149,59	**-9,9**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumulative oil extraction [EJ]	5560,36	6451,85	**-13,9**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Cumulative oil extraction [EJ]	5683,63	6149,59	**-6,7**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Fuel diversity of transport [SWDI]	-0,82	-0,82	**0,0**	2050		x	x	x	x	x	
AMPERE2-450-NucOff-OPT	Fuel diversity of transport [SWDI]	-0,78	-0,82	**-0,1**	2050		x	x	x	x	x	
AMPERE2-450-LimSW-OPT	Fuel diversity of transport [SWDI]	-0,91	-0,90	**-1,3**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Fuel diversity of transport [SWDI]	-1,03	-0,90	**-11,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Fuel diversity of transport [SWDI]	-1,16	-0,88	**-31,2**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	Fuel diversity of transport [SWDI]	-0,63	-0,82	**22,9**	2050		x	x	x	x	x	
AMPERE2-450-FullTech-LST	Fuel diversity of transport [SWDI]	-0,98	-0,82	**-2,8**	2050		x	x	x	x	x	
AMPERE2-450-NucOff-LST	Fuel diversity of transport [SWDI]	-0,99	-0,82	**-1,8**	2050		x	x	x	x	x	
AMPERE2-450-LimSW-LST	Fuel diversity of transport [SWDI]	-0,94	-0,90	**-4,8**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Fuel diversity of transport [SWDI]	-1,09	-0,90	**-14,5**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Fuel diversity of transport [SWDI]	-1,38	-0,88	**-60,6**	2050		x	x				
AMPERE2-450-LowEI-LST	Fuel diversity of transport [SWDI]	-0,93	-0,82	**16,3**	2050		x	x	x	x	x	

AMPERE2-450-FullTech-OPT	Maximum transitional growth reduction	41,09	41,09	**0,0**	2020-50				x		x	x
AMPERE2-450-NucOff-OPT	Maximum transitional growth reduction	45,11	45,15	**33,8**	2020-50				x		x	x
AMPERE2-450-LimSW-OPT	Maximum transitional growth reduction	35,01	35,33	**32,3**	2020-50				x		x	
AMPERE2-450-LimBio-OPT	Maximum transitional growth reduction	42,59	43,66	**107,5**	2020-50				x		x	
AMPERE2-450-NoCCS-OPT	Maximum transitional growth reduction	42,23	43,75	**152,0**	2020-50				x		x	
AMPERE2-450-LowEI-OPT	Maximum transitional growth reduction	41,28	41,02	**-25,7**	2020-50				x		x	x
AMPERE2-450-FullTech-LST	Maximum transitional growth reduction	28,65	30,02	**119,4**	2020-50				x		x	x
AMPERE2-450-NucOff-LST	Maximum transitional growth reduction	28,62	30,07	**144,4**	2020-50				x		x	x
AMPERE2-450-LimSW-LST	Maximum transitional growth reduction	28,35	29,47	**112,5**	2020-50				x		x	
AMPERE2-450-LimBio-LST	Maximum transitional growth reduction	29,83	32,88	**304,3**	2020-50				x		x	
AMPERE2-450-NoCCS-LST	Maximum transitional growth reduction	n/a	n/a	**n/a**	2020-50				x		x	
AMPERE2-450-LowEI-LST	Maximum transitional growth reduction	29,40	28,25	**-3,0**	2020-50				x		x	x
AMPERE2-450-FullTech-OPT	Maxium decadal energy price growth	1,33	1,33	**0,0**	2020-50				x		x	
AMPERE2-450-NucOff-OPT	Maxium decadal energy price growth	1,21	1,19	**1,8**	2020-50				x		x	
AMPERE2-450-LimSW-OPT	Maxium decadal energy price growth	1,40	1,30	**6,8**	2020-50				x		x	
AMPERE2-450-LimBio-OPT	Maxium decadal energy price growth	1,46	1,30	**11,6**	2020-50				x		x	
AMPERE2-450-NoCCS-OPT	Maxium decadal energy price growth	1,62	1,30	**23,4**	2020-50				x		x	
AMPERE2-450-LowEI-OPT	Maxium decadal energy price growth	1,21	1,21	**0,6**	2020-50				x		x	
AMPERE2-450-FullTech-LST	Maxium decadal energy price growth	1,38	1,23	**12,3**	2020-50				x		x	
AMPERE2-450-NucOff-LST	Maxium decadal energy price growth	1,40	1,23	**13,9**	2020-50				x		x	
AMPERE2-450-LimSW-LST	Maxium decadal energy price growth	1,52	1,23	**23,2**	2020-50				x		x	
AMPERE2-450-LimBio-LST	Maxium decadal energy price growth	2,24	1,28	**76,6**	2020-50				x		x	
AMPERE2-450-NoCCS-LST	Maxium decadal energy price growth	n/a	n/a	**n/a**	2020-50							
AMPERE2-450-LowEI-LST	Maxium decadal energy price growth	1,40	1,28	**9,8**	2020-50				x		x	
AMPERE2-450-FullTech-OPT	Share of idle coal capacity	0,41	0,41	**0,0**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Share of idle coal capacity	0,56	0,41	**-1,5**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Share of idle coal capacity	0,35	0,41	**1,1**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Share of idle coal capacity	0,77	0,41	**7,0**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Share of idle coal capacity	0,45	0,21	**7,0**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	Share of idle coal capacity	0,43	0,41	**0,3**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Share of idle coal capacity	0,85	0,41	**24,9**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Share of idle coal capacity	0,81	0,41	**17,8**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Share of idle coal capacity	0,81	0,41	**9,0**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Share of idle coal capacity	0,89	0,41	**19,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Share of idle coal capacity	0,59	0,17	**276,1**	2050		x	x				
AMPERE2-450-LowEI-LST	Share of idle coal capacity	0,83	0,41	**27,1**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	CO_2 captured & stored [Gt]	10844,76	10844,76	**0,0**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	CO_2 captured & stored [Gt]	13638,38	10844,76	**22,4**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	CO_2 captured & stored [Gt]	17328,08	13521,52	**22,4**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	CO_2 captured & stored [Gt]	15836,94	13521,52	**-6,9**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	CO_2 captured & stored [Gt]	0,00	10844,76	**-100,0**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	CO_2 captured & stored [Gt]	6807,59	10844,76	**-36,8**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	CO_2 captured & stored [Gt]	10925,85	10844,76	**-0,2**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	CO_2 captured & stored [Gt]	13307,78	10844,76	**14,5**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	CO_2 captured & stored [Gt]	16728,00	13521,52	**20,0**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	CO_2 captured & stored [Gt]	13920,23	13521,52	**-17,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	CO_2 captured & stored [Gt]	0,00	10844,76	**-100,0**	2050		x	x				
AMPERE2-450-LowEI-LST	CO_2 captured & stored [Gt]	6764,11	10844,76	**-34,0**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Nuclear capacity expansion in Newcomers [in GW]	166,94	166,94	**0,0**	2050			x	x	x	x	x
AMPERE2-450-NucOff-OPT	Nuclear capacity expansion in Newcomers [in GW]	6,70	166,94	**-93,7**	2050			x	x	x	x	x
AMPERE2-450-LimSW-OPT	Nuclear capacity expansion in Newcomers [in GW]	141,73	210,52	**1,9**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Nuclear capacity expansion in Newcomers [in GW]	206,69	210,52	**45,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Nuclear capacity expansion in Newcomers [in GW]	600,81	254,10	**153,3**	2050			x	x		x	
AMPERE2-450-LowEI-OPT	Nuclear capacity expansion in Newcomers [in GW]	86,64	166,94	**-32,4**	2050			x	x	x	x	x
AMPERE2-450-FullTech-LST	Nuclear capacity expansion in Newcomers [in GW]	172,77	166,94	**3,5**	2050			x	x	x	x	x
AMPERE2-450-NucOff-LST	Nuclear capacity expansion in Newcomers [in GW]	6,70	166,94	**-93,7**	2050			x	x	x	x	x
AMPERE2-450-LimSW-LST	Nuclear capacity expansion in Newcomers [in GW]	180,83	210,52	**18,3**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Nuclear capacity expansion in Newcomers [in GW]	255,71	210,52	**56,8**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Nuclear capacity expansion in Newcomers [in GW]	715,12	254,10	**181,4**	2050			x				
AMPERE2-450-LowEI-LST	Nuclear capacity expansion in Newcomers [in GW]	82,56	166,94	**-32,0**	2050			x	x	x	x	x
AMPERE2-450-FullTech-OPT	Bioenergy supply [EJ]	146,83	146,83	**0,0**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Bioenergy supply [EJ]	150,44	146,83	**3,3**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Bioenergy supply [EJ]	168,30	162,96	**3,6**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Bioenergy supply [EJ]	108,54	162,96	**-35,3**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Bioenergy supply [EJ]	170,05	146,83	**11,6**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	Bioenergy supply [EJ]	96,88	146,83	**-30,6**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Bioenergy supply [EJ]	148,49	146,83	**0,3**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Bioenergy supply [EJ]	157,42	146,83	**6,8**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Bioenergy supply [EJ]	168,62	162,96	**3,4**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Bioenergy supply [EJ]	110,83	162,96	**-33,9**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Bioenergy supply [EJ]	216,14	132,83	**56,5**	2050		x	x				
AMPERE2-450-LowEI-LST	Bioenergy supply [EJ]	113,84	146,83	**-30,0**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Maximum PV and wind upscaling	2637,39	2637,39	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Maximum PV and wind upscaling	2631,82	2637,39	**23,5**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Maximum PV and wind upscaling	933,03	2637,39	**-66,3**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Maximum PV and wind upscaling	2737,18	2637,39	**8,8**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Maximum PV and wind upscaling	6079,59	3185,02	**57,3**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Maximum PV and wind upscaling	1033,60	2637,39	**-55,3**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Maximum PV and wind upscaling	2828,07	2637,39	**11,5**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Maximum PV and wind upscaling	2971,95	2637,39	**35,3**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Maximum PV and wind upscaling	1134,66	2637,39	**-57,0**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Maximum PV and wind upscaling	3574,35	2637,39	**49,3**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Maximum PV and wind upscaling	11495,02	2281,02	**268,8**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Maximum PV and wind upscaling	1591,21	2637,39	**-38,6**	2020-50		x	x	x	x	x	x

7 Acronyms and definitions

All acronym and definitions are adapted from Allwood *et al* (2014), mostly following von Stechow *et al* (2015). Blue words indicate that the term is defined in the following:

Adverse side-effects: the potential negative effects of a policy aimed at one objective on other objectives, without evaluating social welfare implications.

Aerosol: a suspension of airborne solid [primary particulate matter (PM)] or liquid particles (secondary PM from gaseous precursors) that may influence climate in several ways.

AFOLU: Agriculture, Forestry and Other Land Use plays a central role for food security and sustainable development (SD).

Black carbon (BC): an aerosol species mostly formed by incomplete fuel combustion, causing a warming effect by absorbing heat into the atmosphere.

Carbon dioxide (CO_2): A naturally occurring gas and by-product of burning fossil fuels and biomass, of land use changes and of industrial processes – the principal anthropogenic greenhouse gas (GHG).

CO_2-equivalent concentration (CO_2eq): The concentration of carbon dioxide (CO_2) that would cause the same radiative forcing as a given mixture of GHGs, aerosols, and surface albedo changes.

Co-benefits: the potential positive effects of a policy aimed at one objective on other objectives, without evaluating social welfare implications.

Conference of Parties (COP): The supreme body of the United Nations Framework Convention on Climate Change (UNFCCC).

Cost-effectiveness analysis (CEA): a tool based on constrained optimization for comparing policies designed to meet a pre-specified target.

Cost-benefit analysis (CBA): monetary measurement of all negative and positive effects associated with a given policy.

Carbon dioxide capture and storage (CCS): Carbon dioxide (CO_2) from industrial and energy-related sources, which is captured, conditioned, compressed, and transported to a long-term storage location.

> Bioenergy and CCS (BECCS): the application of CCS technology to bioenergy conversion processes. Depending on the total lifecycle emissions, BECCS has the potential for net carbon dioxide (CO_2) removal from the atmosphere.

Energy intensity (EI): the ratio of energy use to economic or physical output.

EJ: exajoule

Greenhouse gas (GHG): gaseous constituents of the atmosphere (natural and anthropogenic), which absorb and emit radiation at specific wavelengths emitted, e.g., by Earth's surface.

Gross domestic product (GDP): the sum of gross value added by all producers in an economy for a given period, normally one year.

Hg: mercury

Integrated assessment model (IAM): integrated (assessment) models explore the interactions between multiple sectors of the economy or components of particular systems, such as the energy system. In this letter, we refer to these models as 'integrated models'.

Mitigation (of climate change): reducing the sources or enhancing the sinks of greenhouse gases (GHGs); or reducing other substances that contribute directly or indirectly to limiting climate change.

Mitigation measures: technologies, processes or practices that contribute to mitigation.

Mitigation pathway: The trajectory taken over time to meet different goals for greenhouse gas (GHG) emissions, atmospheric concentrations, or global mean surface temperature change that implies a set of economic, technological, and behavioural changes.

Nitrogen oxides (NO_x): Any of several oxides of nitrogen.

Particulate matter (PM): very small solid particles from solid fuel combustion, which cause adverse health effects and can directly alter the radiation balance.

$PM_{2.5}$: particulate matter 2.5 micrometers in diameter or smaller.

Precursors: atmospheric compounds that have an effect on greenhouse gas (GHG) or aerosol concentrations regulating their production or destruction rates.

Radiative forcing: the change in the net radiative flux at the tropopause due to a change in an external driver of climate change.

Renewable energy (RE): Any form of energy from solar, geophysical, or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use.

Sink: any process, activity, or mechanism that removes a greenhouse gas (GHG), an aerosol, or a precursor of a GHG or aerosol from the atmosphere.

SO_2: sulfur dioxide.

Sustainable development (SD): development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Traditional biomass: fuelwood, charcoal, agricultural residues, and animal dung used with traditional technologies, e.g., open fires for cooking, rustic kilns, and ovens for small industries.

WGIII AR5: Working Group III Contribution to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.

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Annex 3

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Large-scale bioenergy production: how to resolve sustainability trade-offs?

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Abstract

Large-scale 2nd generation bioenergy deployment is a key element of 1.5 °C and 2 °C transformation pathways. However, large-scale bioenergy production might have negative sustainability implications and thus may conflict with the Sustainable Development Goal (SDG) agenda. Here, we carry out a multi-criteria sustainability assessment of large-scale bioenergy crop production throughout the 21st century (300 EJ in 2100) using a global land-use model. Our analysis indicates that large-scale bioenergy production without complementary measures results in negative effects on the following sustainability indicators: deforestation, CO_2 emissions from land-use change, nitrogen losses, unsustainable water withdrawals and food prices. One of our main findings is that single-sector environmental protection measures next to large-scale bioenergy production are prone to involve trade-offs among these sustainability indicators—at least in the absence of more efficient land or water resource use. For instance, if bioenergy production is accompanied by forest protection, deforestation and associated emissions (SDGs 13 and 15) decline substantially whereas food prices (SDG 2) increase. However, our study also shows that this trade-off strongly depends on the development of future food demand. In contrast to environmental protection measures, we find that agricultural intensification lowers some side-effects of bioenergy production substantially (SDGs 13 and 15) without generating new trade-offs—at least among the sustainability indicators considered here. Moreover, our results indicate that a combination of forest and water protection schemes, improved fertilization efficiency, and agricultural intensification would reduce the side-effects of bioenergy production most comprehensively. However, although our study includes more sustainability indicators than previous studies on bioenergy side-effects, our study represents only a small subset of all indicators relevant for the SDG agenda. Based on this, we argue that the development of policies for regulating externalities of large-scale bioenergy production should rely on broad sustainability assessments to discover potential trade-offs with the SDG agenda before implementation.

Introduction

Large-scale bioenergy deployment of up to 300 EJ per year by 2100 is a key element of 1.5 °C and 2 °C transformation pathways [1, 2]. In such ambitious mitigation scenarios, bioenergy is primarily used in combination with carbon capture and storage (CCS), so that energy production simultaneously leads to a removal of carbon dioxide (CO_2) from the atmosphere [3]. When CCS is assumed to be unavailable in low climate stabilization scenarios (reflecting technology failure or missing social acceptance), bioenergy deployment still contributes significantly to climate change mitigation by the substitution of fossil fuels [4].

Like the production of food, the production of bioenergy requires land, water and nutrients. Today's agricultural systems occupy ∼38% of the Earth's ice-free land surface (cropland and pasture), account for ∼70% of global freshwater withdrawals and rely on substantial amounts of reactive nitrogen fixation (about three times the pre-industrial level) [5, 6]. Currently, prevailing practices to increase agricultural production impair the environment [5, 7]. The expansion of agricultural land is a major driver of deforestation [8], which causes CO_2 emissions [9] and threatens biodiversity, especially in the tropics [10]. On the other hand, land-use intensification causes nutrient pollution by increased use of fertilizer, which can harm aquatic and marine ecosystems and contributes to air pollution [5, 7, 11]. Hence, there are currently trade-offs between the provision of food and the maintenance of biodiversity and regulating ecosystem services such as carbon sequestration or water purification [12–14]. Thus, large-scale bioenergy production for climate change mitigation in addition to the provision of food for a growing world population might exacerbate adverse side-effects of agricultural production in the coming decades, which would conflict with the global Sustainable Development Goal (SDG) agenda [15].

One approach to reconcile large-scale bioenergy production with the global SDG agenda are environmental protection measures such as forest or water conservation schemes [16–19]. However, regulating one environmental externality of bioenergy production may interfere with other SDGs [20, 21]. For instance, forest protection may increase competition for land, potentially leading to a rise in food prices.

Another strategy to align large-scale bioenergy production with the SDG agenda could be the implementation of measures reducing the pressure on land in general (land-sparing measures) such as improved agricultural productivity [22] or reduced consumption of resource intensive livestock products combined with less household waste [20].

The existing literature on sustainability trade-offs in the context of global large-scale bioenergy production is mostly limited to land and water conservation schemes [16–19, 23]. Moreover, land and water conservation schemes as well as other measures that could alleviate unwanted side-effects of bioenergy production have not been studied within a consistent analytical framework so far. Our study extends the existing literature in three dimensions. First, we cover more sustainability indicators than previous studies on side-effects of bioenergy production. Second, we investigate more complementary measures (standalone and in combinations) next to large-scale bioenergy production within a consistent analytical framework than previous studies. Third, we analyze the importance of future food demand developments for the effectiveness of such complementary measures.

In this study, we carry out a multi-criteria sustainability analysis to assess how global large-scale bioenergy production may conflict with other sustainability objectives throughout the 21st century and to what extent complementary measures could help to resolve such sustainability trade-offs. Besides forest and water protection schemes, we also investigate to what extend improved fertilization efficiency and agricultural intensification could reduce side-effects of large-scale bioenergy production. We assume identical 2nd generation bioenergy demand across all scenarios (except a baseline scenario without bioenergy demand) to identify the effects of a single measure or a combination of measures on the following sustainability indicators (mapping to SDGs in brackets): deforestation [SDG 15], CO_2 emissions from land-use change (LUC) [SDG 13], nitrogen losses to the environment [SDGs 13, 14, 15], unsustainable water withdrawals [SDG 14], food price index [SDG 2] and bioenergy prices [SDG 7].

The global 2nd generation bioenergy demand trajectory used here increases linearly from 0 EJ in 2010 to 300 EJ in 2100, which reflects the upper end of projections from Integrated Assessment Models (IAMs) for bioenergy deployment in 1.5 °C and 2 °C transformation pathways [1]. With this in mind, our study setup allows to analyze the upper end of environmental and social implications bioenergy crop production may entail under ambitious climate protection. In the IAM projections, high-yielding dedicated 2nd generation bioenergy crops such as grasses (miscanthus) and fast-growing trees (eucalyptus, poplar) play a central role and are also heavily discussed on their potential as well as side-effects [24, 25]. Therefore, we focus on dedicated grassy and woody biomass in this study.

Methods

For our multi-criteria sustainability analysis, we use the global multi-regional land-use optimization model MAgPIE (Model of Agricultural Production and its Impacts on the Environment) [26]. MAgPIE integrates various spatially explicit biophysical factors such as land, yields and available water into an economic decision-making mechanism. In the following, we summarize the key features of MAgPIE, describe the sustainability indicators derived from MAgPIE and introduce our scenario setup. In the supplementary information (SI) available at stacks.iop.org/ERL/13/024011/mmedia, we expand our methods by a detailed general model description, additional details on modelling of bioenergy in MAgPIE, key scenario inputs and more detailed descriptions of the scenario implementations.

Land-use optimization model MAgPIE

MAgPIE is a global multi-regional partial equilibrium model of the land-use sector [27, 28]. The objective function of the model is the minimization of global costs for agricultural production (food and bioenergy) throughout the 21st century (5 year time steps) in recursive dynamic mode (see supplementary figure S1 for an overview). The model is driven by demand for agricultural commodities (supplementary figure S12), which is calculated based on population and income projections for the 21st century from the Shared Socioeconomic Pathways (SSPs) [29]. The production of agricultural commodities is associated with costs for labor, capital, fertilizer, technological change, transport, and land conversion. Demand and costs enter the model at the level of ten world regions (supplementary figure S7, supplementary table S2). To account for trade barriers, the regions have to produce a certain share of their demand domestically [30]. For meeting the demand, the model endogenously decides, based on cost-effectiveness, about the level of intensification (yield-increasing technological change), extensification (LUC), and production relocation (intra-regionally and inter-regionally through international trade) [30, 31]. The model can also be run with exogenous assumptions for crop productivity. In these cases, crop productivity is taken from a model run that was performed with endogenous intensification (see SI section 3.4 for details). The optimization process is subject to various spatially explicit biophysical conditions, which are derived by the global crop growth, vegetation, and hydrology model LPJmL [32, 33]. Due to computational constraints, spatially explicit input (0.5 degree resolution) is aggregated to 700 simulation units for the optimization process based on a k-means clustering algorithm (supplementary figure S2) [34]. Technically, MAgPIE is a non-linear mathematical programming model that is written in GAMS and solved by CONOPT.

Bioenergy in MAgPIE

MAgPIE simulates two types of bioenergy production: 1st and 2nd generation bioenergy. 1st generation bioenergy relies on conventional food crops such as maize and sugarcane. In contrast, 2nd generation bioenergy is provided by dedicated herbaceous and woody lignocellulosic bioenergy crops (such as Miscanthus, Poplar and Eucalyptus), which feature significantly higher yields [35].

Whereas demand for 1st generation bioenergy (and all other agricultural commodities) in MAgPIE is defined for ten economic world regions based on existing policies, 2nd generation bioenergy demand enters the model at the global scale. Spatial allocation of 2nd generation bioenergy production is an endogenous model decision resulting from the cost minimizing objective function, which takes into account land and water availability as well as bioenergy yields and production costs [16, 19, 36]. The SI provides additional details on modelling of bioenergy in MAgPIE (SI sections 1.2 and 2.2)

Table 1. Sustainability indicators derived from MAgPIE for each scenario and mapping of these indicators to SDGs.

Name	Unit	Mapping to SDGs
Deforestation	Mha since 2010	SDG 15 (life on land)
LUC emissions	$GtCO_2$ since 2010	SDG 13 (climate action)
Nitrogen losses	Tg Nr yr^{-1}	SDGs 13, 14 (life below water) and 15
Water use above EF	km yr^{-3}	SDG 14 (life below water)
Food price index	Index (2010 = 1)	SDG 2 (zero hunger)
Bioenergy price	US$2005/GJ	SDG 7 (affordable and clean energy)

Indicators derived from MAgPIE

To identify sustainability trade-offs related to large-scale bioenergy production, we carry out a multi-criteria analysis covering the following six indicators (see table 1). We derive these indicators from MAgPIE for all scenarios listed in table 2 (see next paragraph). To put our analysis in the context of the SDGs, we additionally map each indicator to one or more SDG(s).

Deforestation is calculated as the difference between forest area in each simulation time step and forest area in the reference year 2010 [26].

LUC CO_2 emissions (cumulative) are calculated as the difference between terrestrial carbon stocks in each simulation time step and terrestrial carbon stocks in the reference year 2010 [26]. For instance, if forest is converted to cropland, carbon stocks decline, resulting in CO_2 emissions from LUC.

Nitrogen losses to the environment from cropland soils and animal waste management are calculated based on a nitrogen budget approach [37]. Nitrogen removal in plant biomass depends on crop type and yield-dependent residue production. Soil uptake is estimated as nitrogen removal minus biological fixation by N-fixing plants. Dependent on the soil nitrogen uptake efficiency, which is an exogenous scenario parameter in the model (see SI section 3.2), total nitrogen fertilization requirements are estimated. All available organic nitrogen fertilizers (e.g. manure, crop residues) are used to fulfill the fertilization requirements. Subsequently, the remainder needs to be balanced out by the application of inorganic nitrogen fertilizer. Nitrogen losses are estimated as the difference between crop uptake and organic as well as inorganic fertilizers.

Water use above environmental flow (EF) requirements, i.e. unsustainable water withdrawals, are derived by comparing the sum of human and environmental water demand to available water [38]. In MAgPIE, human water demand consists of domestic, industrial and agricultural water demand. While domestic and industrial water demand are exogenous based on WaterGAP simulations [39, 40], agricultural water demand depends on irrigated crop production, which is dynamic in MAgPIE [30]. In addition,

Table 2. Summary of study design. (*a*) Scenario definitions, (*b*) bioenergy demand and (*c*) parameter settings entering the MAgPIE model. Parameter settings are shown in aggregated form at the global scale (see SI section 3 for details).

a)

Scenario	Bioenergy	Environmental protection and land-sparing measures (P1 to P5 indicate the corresponding parameters; see c)	Expected positive effect on indicator(s)
NoBio	off	–	
Bio	on	–	
Bio-REDD	on	Forest protection by putting a price on CO_2 emissions from the conversion of forests and other carbon-rich ecosystems (P1)	deforestation, LUC emissions
Bio-EffNfert	on	Improved soil nitrogen uptake efficiency (P2)	nitrogen losses
Bio-WaterProt	on	Protection of water resources based on environmental flow requirements (P3)	water use above EF
Bio-IntensAg	on	Higher food and bioenergy crops yields (P4) and higher livestock productivity (P5)	deforestation, LUC emissions food price index, bioenergy price
Bio-All	on	Combination of *REDD, EffNfert, Water-Prot and IntensAg* (P1-P5)	all

b)

	2010	2015	2030	2040	2050	2075	2100
Bioenergy demand (EJ yr^{-1})	0	17	67	100	133	217	300

c)

		No measure (default)				*Measure*		
Parameter ID and name		**2010**	**2030**	**2050**	**2100**	**2030**	**2050**	**2100**
P1	CO_2 price in US$/t$CO_2$	0	0	0	0	24	65	743
P2	Soil nitrogen uptake efficiency [37]	53%	57%	60%	60%	65%	75%	85%
P3	Environmental flow protection [38]	off				on		
P4	Yield-increasing technological change (food and bioenergy crops) [31]	exogenous (based on *NoBio*)				endogenous; resulting in higher crop yields		
P5	Livestock productivity	medium				high		

irrigation infrastructure can be extended endogenously based on cost-effectiveness [30]. The required water for irrigation is proportional to the production volume. Environmental water demand is based on spatially explicit environmental flow requirements (Smakhtin algorithm) [38]. Available water, also spatially explicit, is derived from LPJmL [32, 33].

The **food price index** weights current prices based on current food baskets (Paasche price index) [41]. The food prices used for calculating the food price index are shadow prices, taken from the regional food demand constraint in the model (see SI section 1.1 for details on shadow prices).

Bioenergy prices are also shadow prices, taken from the global bioenergy demand constraint in the model, and thus reflect the changes in the aggregate world market price for 2nd generation bioenergy feedstocks [19].

In the supplementary information, we compare the absolute level and trend of these indicators or appropriate proxies with observed data (supplementary figures S20–S27).

Scenarios run with MAgPIE

To investigate environmental and socio-economic effects of large-scale bioenergy production with and without accompanying measures, we run the following scenarios with MAgPIE (table 2).

The general setup of our scenarios including food demand is based on the SSP2 'middle-of-the-road' storyline for the land use sector, which represents a continuation of current social, economic, and technological trends into the future [42]. All scenarios include the same 1st generation bioenergy demand trajectory. The SI provides more details on key scenario inputs (e.g. food and bioenergy demand).

We start by comparing a scenario with 2nd generation bioenergy demand (*Bio*) to a scenario without 2nd generation bioenergy demand (*NoBio*).

Subsequently, we analyze scenarios combining 2nd generation bioenergy demand and single measures aimed at alleviating particular negative side-effects of bioenergy production. The guiding principle behind our scenario design is to have one measure with expected positive effects for each sustainability indicator. These scenarios include: a forest protection scenario (*Bio-REDD*) to lower deforestation and associated LUC emissions, a scenario with improved fertilization techniques (*Bio-EffNfert*) to lower nitrogen losses, a water protection scenario (*Bio-WaterProt*) to lower water use above EF. In addition to these protection scenarios, we assess a scenario with higher crop yields and livestock productivity (*Bio-IntensAg*), which reduces the overall pressure in the land-use system. We expand on the motivation of these scenarios in the results section. The SI provides details for each scenario implementation (i.e. for *REDD*, *EffNfert*, *WaterProt* and *IntensAg*).

Finally, we estimate the effects of combining 2nd generation bioenergy production with all the above measures (*Bio-All*).

The measures we analyze in combination with 2nd generation bioenergy production could also help to lower side-effects of agricultural production in general. To investigate these effects, we run all scenarios listed in table 2 additionally without 2nd generation bioenergy (see SI section 6).

Our scenario setup (table 2) includes bioenergy scenarios with single measures (e.g. *Bio-REDD*) and all four measures together (*Bio-All*). To decompose the interactions of measures on indicator outcomes, we additionally test all combinations of measures possible (e.g. *Bio-REDD-WaterProt* or *Bio-REDD-WaterProt-IntensAg*).

To facilitate straightforward comparison of these scenario results we calculate a normalized score (based on [23]) for each sustainability indicator at the global scale. The score ranges between 0 and 1, in which 0 is the worst outcome across all scenarios in year 2100 for a particular indicator and 1 is the best outcome. In addition, we sort the scenarios according to the sum of indicator scores. For the six indicators we consider here (see table 1), the best possible scenario has a score sum of 6 (all six indicators have a score of 1), whereas the worst scenario has a score sum of 0.

Importance of food demand

Future food demand is seen as a key driver for the development of the agricultural sector [42]. To evaluate the stability of our results we run all scenarios listed in table 2 with SSP1 (sustainable development) and SSP5 (fossil-fueled development) food demand in addition to our default SSP2 (middle-of-the-road) setting. Total food demand, and hence overall pressure in the land-use sector, is increasing from SSP1 to SSP2 to SSP5 (see SI). For analyzing the results of these scenarios, we apply the normalized score approach described above, with the difference that the score for each indicator is calculated across scenarios, time steps and food demand scenarios.

Results

Adverse side-effects of large-scale bioenergy crop cultivation

Our modelling results indicate that rising production of bioenergy crops for climate change mitigation throughout the 21st century gradually increases the number and magnitude of negative global environmental externalities (*Bio* scenario). Global 2nd generation bioenergy crop area amounts to 180 Mha in 2030 (67 EJ), 312 Mha in 2050 (133 EJ) and 636 Mha in 2100 (300 EJ). The absolute increase of global cropland needed to accommodate additional food, feed and bioenergy crop production between 2010 and 2030 amounts to 441 Mha, which is a relative increase of cropland by 27% (global cropland in 2010 is 1617 Mha) (figure 1). In the absence of bioenergy deployment (*NoBio* scenario), cropland increases only by 231 Mha (14%). Cropland mainly expands into pasture and forest areas. Global pasture/forest area (2968/4152 Mha in 2010) declines between 2010 and 2030 by 234/147 Mha under bioenergy deployment (*Bio* scenario) compared to 133/60 Mha without (*NoBio* scenario). Cropland expansion into pasture, forest and other natural vegetation for food and bioenergy production results in global cumulative emissions of 146 Gt CO_2 between 2010 and 2030 (*Bio* scenario), compared to 57 Gt CO_2 without bioenergy (*NoBio* scenario) (figure 2(*a*)). Thus, the impact of providing 67 EJ bioenergy in 2030 is more than a doubling of global LUC CO_2 emissions. By 2050, global annual bioenergy demand increases to 133 EJ in our scenarios, which causes a rise in nitrogen losses due to increased fertilizer use (+16%) and water use above EF (+49%) besides higher LUC emissions (+180%); numbers are relative to the *NoBio* baseline scenario in 2050 (figure 2). By 2100, when global bioenergy demand reaches 300 EJ yr^{-1}, adverse side-effects of bioenergy crop production further increase. Not only the global environmental indicators, such as LUC emissions (+437%), nitrogen losses (+34%) and water use above EF (+142%) rise, but also food prices are 28% higher (figure 3(*a*)). Thus, our results indicate that large-scale bioenergy production conflicts partly with SDGs 2, 13, 14 and 15 in the absence of complementary measures. The supplementary data provides for each scenario listed in table 2 detailed numerical results.

According to our modelling results, the most important regions for bioenergy production are Sub-Saharan Africa (AFR) and Latin America (LAM), which together account for more than 50% of global bioenergy production (supplementary figure S28). As a consequence, AFR and LAM are those regions that face the strongest environmental impacts of bioenergy crop production throughout the 21st century in terms forest loss, CO_2 emissions from LUC, nitrogen losses and unsustainable water withdrawals (supplementary figures S29–S32). Moreover, LAM shows the strongest increase in food prices among all regions (supplementary figure S33).

The positive LUC emissions due to biomass production have to be seen in comparison with CO_2 emission reductions and offsets resulting from the use of biomass in the transport and energy sector [4, 43]. As the combustion of biomass releases only carbon back to the atmosphere that was sequestered before through the growth of biomass on the field, the substitution of fossil fuels by biofuels can reduce CO_2 emissions in the transport sector. Moreover, the combination of biomass-based energy generation with CCS technology can provide energy and remove carbon dioxide from the atmosphere at the same time. According to our scenario results, global cumulative LUC emissions attributable to biomass production (300 EJ in 2100) amount to 293 $GtCO_2$ by 2100. Klein *et al* project that large-scale deployment of bioenergy with CCS

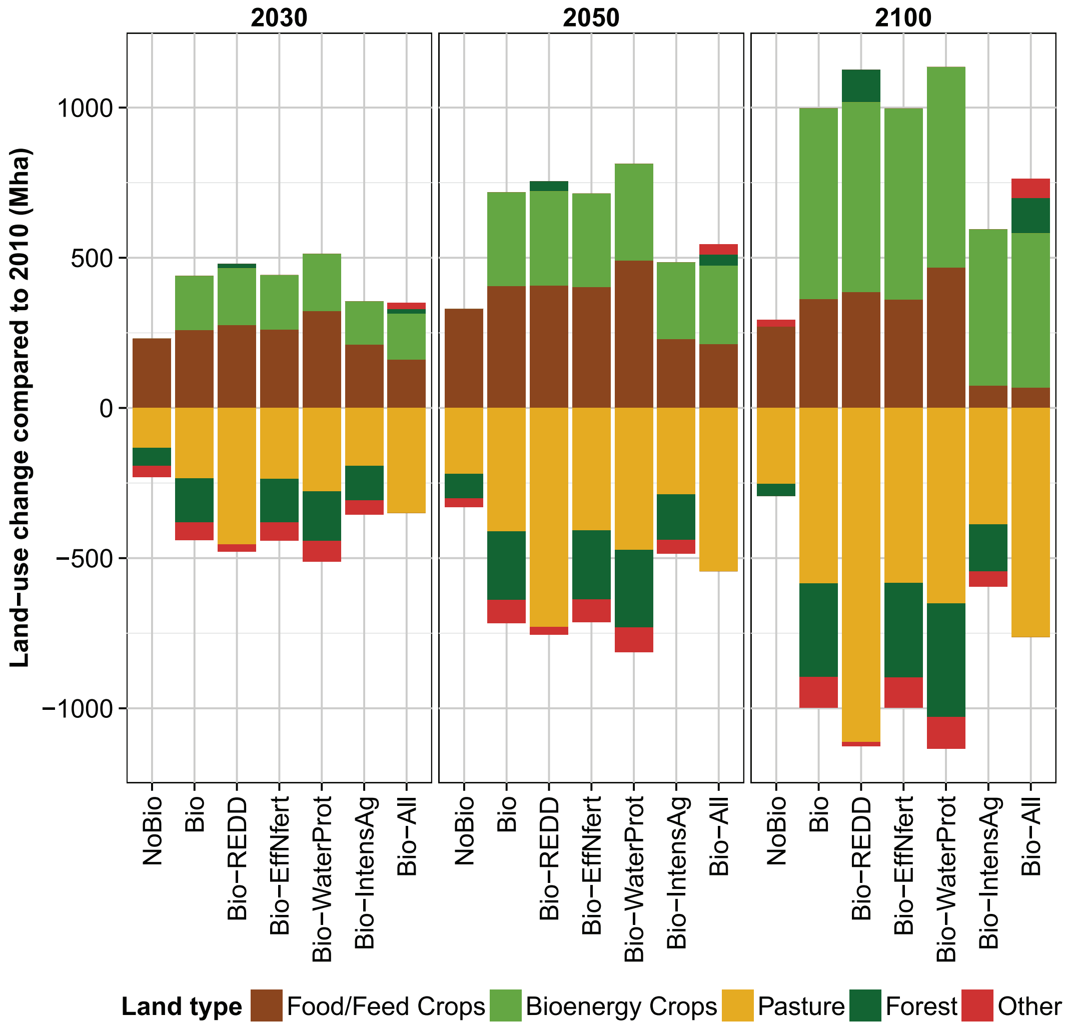

Figure 1. Scenario results for global land-use change in 2030, 2050 and 2100 compared to 2010. Colors depict different land types. Global land cover in 2010 amounts to 1581 Mha for cropland (food/feed crops), 2994 Mha for pasture, 4157 Mha for forest and 4175 Mha for other land (12907 Mha in total).

(300 EJ in 2100) could remove 830 $GtCO_2$ from the atmosphere by 2100 globally [4]. Hence, the carbon debt of biomass production can be expected to be offset over time by bioenergy use with CCS.

Single measures

Reduced Emissions from Deforestation (REDD+) To avoid losses of biodiversity and carbon-rich forest ecosystems mainly due to agricultural expansion, the REDD+ scheme has been adopted under the UNFCCC (United Nations Framework Convention on Climate Change) [44]. Here, we combine a REDD+ scheme with large-scale bioenergy crop production to analyze the repercussions in the agricultural system. In the corresponding *Bio-REDD* scenario, expansion of agriculture into forests and other carbon-rich ecosystems is restrained by putting a price on CO_2 emissions from LUC (figure 1). As a consequence, global cumulative CO_2 emissions from LUC are substantially lower compared to the case without forest protection (*Bio* scenario) (figure 2(*a*)). However, the global food price index rises stronger if bioenergy production is accompanied by a forest protection scheme, which limits the land that is available for agricultural expansion (figure 3(*a*)). Hence, a REDD+ scheme increases the competition for land between food and bioenergy production, which results in higher food prices. Besides food prices, also bioenergy prices rise (figure 3(*b*)). The food price index under a REDD+ scheme particularly increases in developing and emerging economies such as Southern Asia (SAS), Latin America (LAM) and Sub-Saharan Africa (AFR), while price increases in industrialized economies are more modest (supplementary figure S33). Hence, large-scale bioenergy production complemented by a global forest protection scheme (SDGs 13 and 15) might exacerbate conflicts with food security (SDG 2), in particular in developing economies.

Improved fertilization techniques At the global scale, only about half of the inorganic nitrogen fertilizer applied to soils is taken up by crops, while the remainder is lost to the environment causing a cascade of environmental problems [37, 45]. An improvement of the nitrogen use efficiency (NUE) [46] has been

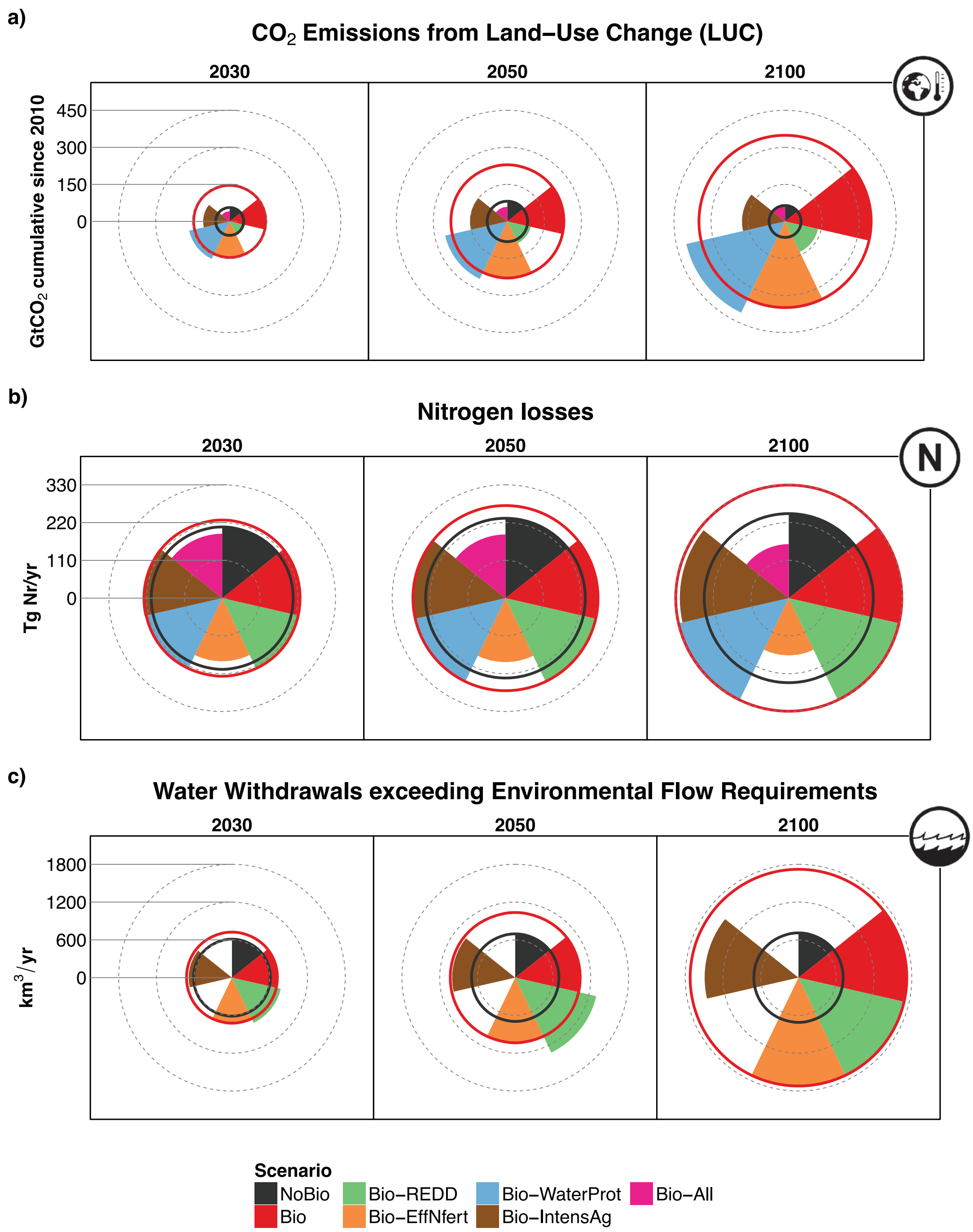

Figure 2. Environmental indicators for 2030, 2050 and 2100 at the global scale. (*a*) CO_2 emissions from LUC, (*b*) nitrogen losses and (*c*) water withdrawals exceeding environmental flow requirements. Solid black circles mark indicator levels without bioenergy production (*NoBio* scenario). For scenarios with bioenergy production, values outside black circles indicate adverse side-effects of bioenergy production (e.g. LUC CO_2 emissions in *Bio*). The environmental protection and land-sparing measures included our scenarios apply not only on bioenergy production but on agricultural production in general. Hence, co-benefits can occur, which are indicated by scenario results located inside black circles (e.g. nitrogen losses in *Bio-EffNfert*). Solid red circles mark indicator levels of bioenergy production without complementary measures (*Bio* scenario). If scenario results are located outside solid red circles for a particular indicator, the underlying measure increases adverse-side effects of agricultural production in this dimension, i.e. the measure, which may successfully lower other impacts, involves a new sustainability trade-off (e.g. LUC CO_2 emissions in *Bio-WaterProt*). The supplementary data provides detailed numerical results.

proposed to alleviate the negative consequences of nitrogen pollution by '*fertilizing the right amount of the right fertilizer at the right time and right place (4R)*' [37]. In our *Bio-EffNfert* scenario, which combines such improved fertilization techniques with bioenergy cultivation, global nitrogen losses amount to 165 Tg Nr yr^{-1} by 2100 (figure 2(*b*)), which is substantially lower compared to the *Bio* (324 Tg Nr yr^{-1}) and even to the *NoBio* scenario (242 Tg Nr yr^{-1}). Nitrogen losses in the *Bio-EffNfert* scenario are lower than in the absence of bioenergy because improved fertilization techniques benefit not only bioenergy but also food crop cultivation. Our results suggest that improved fertilization efficiency has no implications for other

Figure 3. Socio-economic indicators for 2030, 2050 and 2100 at the global scale. (*a*) food price index and (*b*) bioenergy prices. See caption of figure 2 for the interpretation of circles.

indicators except nitrogen losses (SDGs 13, 14 and 15). Land and water use remain unchanged because the same production just requires less nitrogen fertilizer (figure 2). Prices are not affected because we assume that production costs remain constant under more efficient fertilization (figure 3).

Protection of freshwater ecosystems To prevent further degradation of freshwater ecosystems it has been proposed to limit human water withdrawals to a level compatible with local environmental flow requirements (water required to maintain the ecosystem functions of rivers and lakes) [38, 47]. Our *Bio-WaterProt* scenario combines such a water protection scheme with bioenergy cultivation. However, the sustainable use of water in this scenario (figure 2(*c*)) comes at the cost of increased cropland expansion into pasture and forest areas (figure 1) because less water is available for irrigation of food and bioenergy crops. Global bioenergy crop area increases to 667 Mha by 2100, compared to 636 Mha in the *Bio* scenario without environmental flow protection. Deforestation increases in particular in Sub-Saharan Africa (AFR) (supplementary figure S29). By 2100, increased cropland expansion in the *Bio-WaterProt* scenario results in higher global cumulative LUC emissions (425 Gt CO_2) than in the *Bio* scenario (349 Gt CO_2) (figure 2(*a*)). Therefore, our results indicate that accompanying large-scale bioenergy crop production with a water protection scheme (SDG 14) involves a trade-off with the protection of terrestrial ecosystems and its carbon stocks (SDGs 13 and 15).

Increases in agricultural productivity More efficient crop and livestock production systems can effectively lower the need for further expansion of agricultural land into natural ecosystems [20, 22]. Here, we explore to what extent such land-sparing measures could reduce unwanted side-effects of large-scale bioenergy crop production (*Bio-IntensAg* scenario). If higher investments in agricultural research and development (R&D) lead to higher crop yields along with increased livestock productivity (supplementary figures S18 and S19), total cropland expansion for food and bioenergy production into forests and other natural ecosystems is about halved (figure 1). Global bioenergy crop area declines to 520 Mha in 2100 compared to 636 Mha in the *Bio* scenario. Reduced land expansion results in a reduction of global LUC emissions comparable to the *Bio-REDD* scenario with explicit forest protection (figure 2(*a*)). At the same time, the global food price index is similarly low as under no

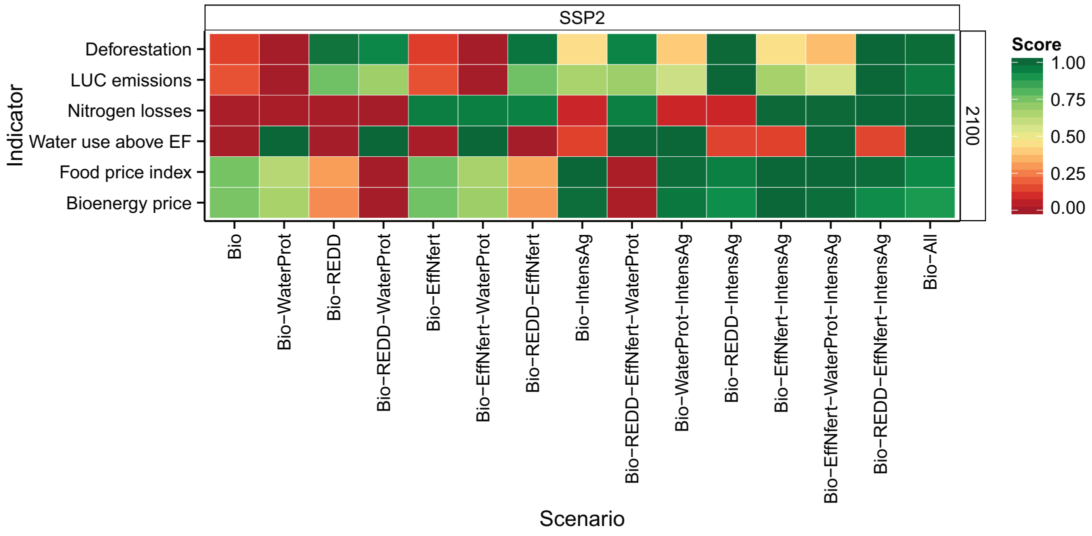

Figure 4. Additional scenarios with all possible combinations of measures considered in our study (see table 2). Results are shown for year 2100 at the global scale. To facilitate straightforward comparison of scenario outcomes across all indicators, we calculate for each indicator normalized scores ranging between 0 and 1. First we determine the worst (0) and the best outcome (1) for each indicator across all scenarios and then align all outcomes in-between accordingly. Finally, we sort the scenarios according to the sum of the six indicator scores (best scenario is on the right-hand side).

bioenergy production because of higher flexibility in how rising food demand is met (figure 3(*a*)). Thus, if large-scale bioenergy production is complemented by R&D-driven increases in agricultural productivity, deforestation and LUC emissions decrease (SDGs 13 and 15) without negative effects on food prices (SDG 2). However, nitrogen losses and unsustainable water withdrawals remain at relatively high levels under increased agricultural productivity (figure 2(*c*)).

Combination of measures

Our analysis indicates that no single measure can alleviate the various adverse side-effects of large-scale bioenergy production simultaneously (figures 2 and 3). Moreover, in some cases the reduction of one externality involves trade-offs with other sustainability objectives (e.g. higher food prices under a forest protection scheme or higher LUC CO_2 emissions under a water protection scheme). Combining all environmental protection (*REDD*, *EffNfert*, *WaterProt*) and land-sparing measures (*IntensAg*) considered in our study reduces environmental and social externalities of large-scale bioenergy production most comprehensively (*Bio-All* scenario). Global bioenergy crop area (513 Mha in 2100) as well as food crop area are comparable to results of the *Bio-IntensAg* scenario (figure 1). In addition, the *REDD* scheme prevents land expansion into forests and other natural lands. As a consequence, global LUC CO_2 emissions are comparable to the *NoBio* scenario without 2nd generation bioenergy (figure 2(*a*)). Moreover, nitrogen losses are halved compared to the *NoBio* scenario (figure 2(*b*)), and water withdrawals do not exceed environmental flow requirements (figure 2(*c*)). At the same time food prices are not affected (same level as in *NoBio*) and bioenergy prices are similar to a scenario without complementary measures (*Bio* scenario) (figure 3). Hence, the combination of environmental protection and land-sparing measures investigated here avoids additional sustainability trade-offs (i.e. no additional conflict with SDGs 2, 7, 13, 14 and 15) under large-scale bioenergy production.

Our scenario analysis shows that a combination of several measures aimed at alleviating side-effect of large-scale bioenergy production(*Bio-All*) results in better overall indicator outcomes than single measures (e.g. *Bio-REDD*). Based on this result, one could draw the conclusion that more measures always result in better indicator outcomes. To test this hypothesis, we additionally run scenarios with all possible combinations of measures considered in our study, calculate normalized scores for each indicator across all scenarios and finally sort the scenarios based on the sum of indicator scores (see methods for details). It turns out that indeed a scenario with four measures (*Bio-All*) achieves the best overall indicator outcome (figure 4). But of the three scenarios with three measures only those two which include intensive agriculture (*IntensAg*) are the next best. The three measure scenario including only environmental protection measures (*Bio-REDD-EffNfert-WaterProt*) performs worse than two-measure scenarios combining environmental protection and intensive agriculture (e.g. *Bio-REDD-IntensAg*). Moreover, *Bio-IntensAg* is the best single measure scenario and performs better than any scenario with two environmental protection measures.

Therefore, more measures do not in all cases increase overall sustainability indicator scores. Instead, the type and mixture of measures matters. Our results indicate that in particular agricultural intensification, which reduces the overall pressure in the agricultural system, is a robust strategy (standalone and

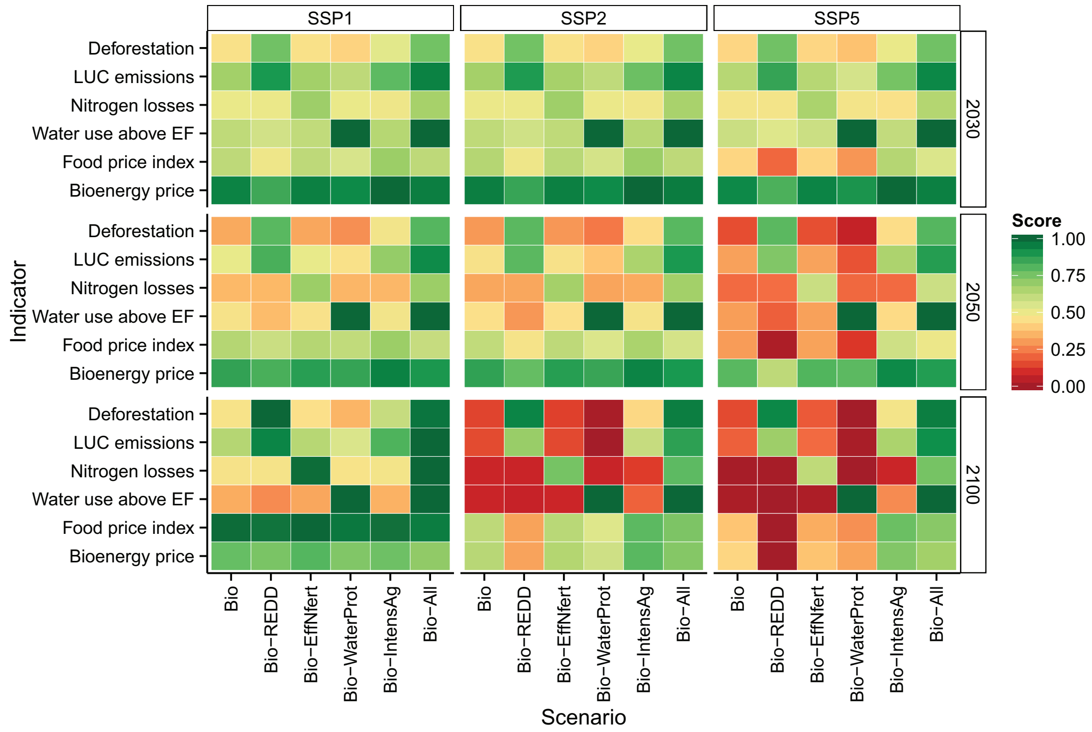

Figure 5. Scenario results for SSP1, SSP2 and SSP5 food demand. To facilitate straightforward comparison of scenario outcomes across all indicators, we calculate for each indicator normalized scores ranging between 0 and 1. First we determine the worst (0) and the best outcome (1) for each indicator across time, scenarios and SSPs and then align all outcomes in-between accordingly.

in combination with other measures) to alleviate unwanted side-effects of large-scale bioenergy cultivation.

Importance of food demand

The indicator scores shown in figure 5 (see methods for calculation) for SSP2 food demand reflect the numerical results presented before. For instance, between *Bio* and *Bio-REDD* the scores for deforestation and LUC emissions increase (positive effect), while the score for the food price index decreases (negative effect).

Under SSP2 food demand there is a general trend of decreasing indicator scores over time, i.e. side-effects increase with increasing bioenergy demand over time. Under SSP5 food demand we observe the same trend but with a stronger signal. In contrast, under SSP1 food demand there is a trend of increasing indicator scores between 2050 and 2100, i.e. side-effects decrease with increasing bioenergy demand over time. In particular, there are no trade-offs under SSP1 food demand between the six sustainability indicators for all measures (except for *Bio-WaterProt*). For instance, a forest protection scheme next to large-scale bioenergy production (*Bio-REDD*) under SSP1 food demand results in reduced deforestation and emissions from land-use change without negative effects on food prices.

These results can be explained by the difference in food demand trajectories between SSP1, SSP2 and SSP5. Our food demand trajectories are based on SSP population and income projections for the 21st century and additionally account for behavioral changes (e.g. reduced per-capita demand for livestock products in SSP1) (see SI for details). Total food demand increases in SSP2 and SSP5 throughout the 21st century, which increases the challenge within the agricultural system to accommodate large amounts of bioenergy production next to food production. In contrast, food demand decreases in SSP1 after 2050, which frees up resources for bioenergy crop cultivation.

Discussion

In this study, we carry out a multi-criteria sustainability assessment of large-scale bioenergy crop production (300 EJ in 2100) throughout the 21st century with and without accompanying measures using the global land-use optimization model MAgPIE.

Our analysis indicates that large-scale bioenergy production without complementary measures under SSP2 food demand results in negative effects on the following sustainability indicators: deforestation, LUC CO_2 emissions, nitrogen losses, unsustainable water withdrawals and food prices. Moreover, our results for SSP2 food demand suggest that single-sector environmental protection measures, if implemented successfully at the global scale, can reduce specific unwanted side-effect of bioenergy production but might exacerbate other environmental or social externalities in some cases. For instance, if large-scale bioenergy production is accompanied by a global forest protection scheme (*Bio-REDD*), deforestation and LUC CO_2 emissions (SDGs 13 and 15) decline substantially whereas food prices (SDG 2) increase. Another trade-off emerges if large-scale bioenergy production is accompanied by a global water protection scheme (*Bio-WaterProt*). In this case, reduced water use in agriculture (SDG 14) comes at the cost of increased deforestation and LUC CO_2 emissions (SDGs 13 and 15). These findings are qualitatively in line with previous studies, which analyze side-effects of large-scale bioenergy production or the implications of environment protection measures next to large-scale bioenergy production [16, 18, 23, 24, 48].

In line with existing literature, our study shows that the trade-off between bioenergy crop area expansion and food prices depends on the underlying socio-economic development [49]. If food demand is decreasing after 2050, as is the case under SSP1 (sustainable development), the trade-off is rather small because bioenergy crops can be grown on cropland previously used for food crop production. In contrast, under SSP5 (fossil-fueled development), which entails higher demand for resource intensive livestock products, the trade-off between agricultural land expansion and associated LUC CO_2 emissions, and food prices is even stronger compared to SSP2 (middle-of-the-road).

In addition to environmental protection measures, we also investigate the sustainability effects of agricultural intensification under large-scale bioenergy production. Our results indicate that agricultural intensification, which lowers the overall pressure in the agricultural system, reduces deforestation and LUC CO_2 emissions (SDGs 13 and 15) substantially without food price (SDG 2) increases, hence avoiding additional trade-offs. This finding partly agrees with the current literature. A recently published study on sustainable development finds that yield increases are a robust strategy to keep food prices in check [23].

Finally, a combined setting of forest and water protection schemes, improved fertilization efficiency, and agricultural intensification next to large-scale bioenergy production performs best across all sustainability indicators. But our analysis also shows that more measures are not always better. In particular a combination of environmental protection measures is prone to have negative effects on food prices. In contrast, agricultural intensification emerges as robust strategy (standalone and in combination with other measures) to lower side-effects of large-scale bioenergy production without additional sustainability trade-offs—at least among those sustainability indicators we consider here.

The environmental and social benefits of the measures investigated here are much stronger in the absence of large-scale 2nd generation bioenergy production (supplementary figure S35). But the importance of these measures increases with demand for land, water and nutrients from land-based mitigation, such as large-scale bioenergy production, in addition to food demand.

Modelling large-scale bioenergy production

Bioenergy can be produced in many different ways, all of which are associated with different potentials and side-effects [24]. In this study, we focus on dedicated grassy and woody biomass as feedstock because of their high productivity and their importance in ambitious mitigation scenarios [24, 50].

We assume that bioenergy crop production competes with food/feed crop production for fertile land. If bioenergy crop production would be limited to degraded land, competition for land and associated side-effects would be lower [51]. However, the global potential of dedicated bioenergy crops grown on degraded land is far below the amount of bioenergy required in ambitious mitigation scenarios [51]. The same holds true for the bioenergy potential of crop residues, forestry residues and waste [52].

Moreover, we assume exogenous global 2nd generation bioenergy crop demand of 133 EJ yr^{-1} in 2050 and 300 EJ yr^{-1} in 2100, which is in line with the upper end of projections from IAMs for bioenergy deployment in 1.5 °C and 2 °C transformation pathways [1]. A bottom-up study based on net primary productivity (NPP) suggests an upper biophysical limit for primary bioenergy of about 190 EJ yr^{-1} in 2050 globally (assuming that bioenergy crops are grown outside existing croplands, infrastructure, wilderness and denser forests) [53]. If sustainability criteria are considered, the maximum global potential to grow dedicated bioenergy crops is estimated 133 EJ yr^{-1} in 2050 on average, based on three studies with completely different methods (intensification of grazing areas, constraints on land and water resources in a dynamic global vegetation model, study with an IAM considering constraints such as soil degradation and water scarcity) [52]. Thus, our assumptions on 2nd generation bioenergy crop production in 2050 do not conflict with biophysical limits from the literature but are at the upper end of bioenergy potential estimates considering sustainability criteria.

Our SSP2-based projections for global 2nd generation bioenergy crop area of 513–667 Mha in 2100 are well within the range of 195−1085 Mha (marker model estimate: 687 Mha) reported by an IAM intercomparison project for an SSP2 RCP 2.6 scenario (RCP 2.6 is consistent with a 2 °C transformation pathway) [42].

Scenario assumptions

In this study, we investigate four different measures in combination with large-scale bioenergy production, each focusing on different sustainability aspects (see table 2). The choice of these measures is based on the current literature discussing side-effects of large-scale bioenergy cultivation [16–19, 23]. All measures we analyze here build on previously published work with the MAgPIE model (see SI for details).

Our scenarios with environmental protection measures can be considered as very optimistic worlds (*REDD*, *EffNfert*, *WaterProt*). These 'policy' scenarios are complemented by a scenario with business-as-usual assumptions for the respective domains (*Bio* scenario). Therefore, our scenario results reflect the range between business-as-usual and very optimistic development at the global scale. For instance, we assume either no protection of environmental flows (*Bio* scenario) or immediate global protection of environmental flows (*Bio-WaterProt* scenario). Similarly, we assume either no CO_2 price (*Bio* scenario) or an immediate globally uniform CO_2 price on emissions from deforestation (*Bio-REDD* scenario).

The real-world implementation of such ambitious environmental protection measures would require well-working governmental institutions at global scale. Therefore, more realistic scenarios would account for regional and temporal delay of implementation (e.g. no CO_2 price in developing countries until 2030). However, our scenario design allows to estimate the order of magnitude of potential positive and negative effects associated with a particular measure.

Besides environmental protection measures, we also analyze a scenario with agricultural intensification (*IntensAg*). Our results indicate that agricultural intensification is a robust strategy (standalone and in combination with other measures) to lower side-effects of large-scale bioenergy production without additional sustainability trade-offs. But to achieve the productivity improvements assumed in our scenario, long-term investments in agricultural R&D would be needed. It is estimate that the average lag of positive effects owing to public investments in agricultural R&D is 15–25 years [54]. Therefore, to buffer potential negative consequences of future bioenergy production governments would need to invest in agricultural R&D already today.

Limitations of sustainability indicators

Our study illustrates the potential consequences of large-scale bioenergy production for a limited set of indicators. But large-scale bioenergy crop production may have other side-effects that are not considered in our study [55]. For instance, bioenergy production, especially if highly-intensified, may further increase phosphorus fertilizer use, thereby threatening rivers, lakes, and coastal oceans with eutrophication [56]. Further examples are impacts on biodiversity from LUC, increased energy requirements for the production of synthetic fertilizer and distributional issues arising from the concentration of profits from bioenergy production [24]. Accounting for such additional dimensions likely increases the number of sustainability trade-offs. Besides negative side effects, bioenergy production may also have some co-benefits not covered in this study. For instance, higher agricultural prices due to land competition may increase farm income [57]. Hence, bioenergy production may also create new income sources in rural areas.

In the following we discuss limitations of the sustainability indicators used in our study.

Deforestation and LUC CO_2 emissions Our study does not include impacts of climate change on crop yields. If crop yields are affected by climate change, this may have repercussion on cropland expansion, and in consequence on deforestation and LUC CO_2 emissions. The results of a multi-model climate change assessment for major crops indicate strong negative effects of climate change, especially at higher levels of warming and at low latitudes [58]. In our scenarios, we assume large-scale bioenergy deployment consistent with ambitious climate targets (i.e. consistent with low levels of global warming). Therefore, such impacts of climate change on crop yields likely play a minor role for our scenario results. Only for the reference scenario without bioenergy (*NoBio*) climate change impacts could be of higher importance. However, even in this case climate impacts are not necessarily higher if mitigation action in other sectors (e.g. energy system) is increased to compensate for missing bioenergy deployment.

Nitrogen losses In MAgPIE, nitrogen losses largely depend on organic and inorganic fertilizers as well as the soil nitrogen uptake efficiency, which is a scenario parameter (see methods and SI section 3.2). The endogenous calculation of nitrogen fertilization in MAgPIE partly accounts for interactions with crop irrigation, which reflects the result of field studies showing that successful yield improvements require the right mix of additional nitrogen fertilizer and additional water [59, 60]. If crops get irrigated in MAgPIE, their yields increase. In our approach, this also implies that farmers adapt their fertilization to this higher yield and increase the nitrogen inputs, resulting in higher nitrogen losses. However, higher nitrogen leaching losses in irrigated systems are not accounted for. Moreover, we assume that intensification of crop production is reached through improved nutrient management, i.e. crop yields increase without a negative impact on nitrogen uptake efficiency. Beyond, intensification can also be reached through applying more nutrients without improving the general management; this will lead to declining marginal returns to fertilization and a falling nitrogen uptake efficiency [61].

Water use above EF The indicator *water use above EF* depends on human and environmental water demand as well as available water (see methods). Agriculture accounts for about 70% of current human water withdrawals [62] and a considerable share of the water intended for irrigation is lost due to bad management, losses in the conveyance system, and inefficient application to the plant [63]. Therefore, improving irrigation efficiency is one of the main options to reduce human water consumption [64]. In our scenarios, we assume a global static value for irrigation efficiency of 66%. This value is the global weighted average of water losses from source to field (conveyance efficiency times management factor) from [65]. Irrigated area from [66] has been used as aggregation weight. We acknowledge that the assumption of static irrigation efficiency throughout the 21st century is rather on the pessimistic side. Sensitivity analysis in the SI (section 7, figure S36) shows how improvements of irrigation efficiency in the course of the 21st century affect our modelling results. If environmental flow protection is combined with increasing irrigation efficiency, the trade-off between land and water resource protection (*Bio-WaterProt* scenario) is strongly reduced because higher deforestation and CO_2 emissions caused by environmental flow protection are partly buffered by improvements in irrigation efficiency.

Food price index and bioenergy prices The food price index as well as bioenergy prices are based on shadow prices derived from MAgPIE (see methods). Shadow prices are directly linked to the objective function of the model, which is minimization of total global production costs (see SI section 1.1). The model currently includes costs for labor, capital, fertilizer, technological change, intraregional transport, land conversion and CO_2 emissions, which implies that only these costs are reflected in shadow prices. Important cost types not included in the model are for instance transaction costs associated with the implementation of environmental protection measures such as forest or water protection schemes. In the case of improved fertilization techniques, however, one could argue that the costs for adopting improved fertilization techniques are offset by the cost savings due to reduced fertilizer requirements.

Conclusion

Our study highlights the challenging task of aligning large-scale bioenergy crop production with the global SDG agenda. In line with previous studies, our analysis indicates that large-scale bioenergy production without complementary measures results in negative effects on the following sustainability indicators: deforestation, LUC CO_2 emissions, nitrogen losses, unsustainable water withdrawals and food prices. One of our main findings is that single-sector environmental protection measures next to large-scale bioenergy production are prone to involve trade-offs with other sustainability objectives—at least in the absence of more efficient land or water resource use. For instance, our results indicate that a global forest protection scheme next to large-scale bioenergy production would substantially lower deforestation and LUC emissions (SDGs 13 and 15) at the cost of higher food prices (SDG 2). However, our study also shows that the existence and magnitude of this trade-off strongly depends on the development of future food demand, which is subject to population and income dynamics as well as dietary changes. In contrast to environmental protection measures, agricultural intensification emerges as a robust strategy (standalone and in combination with other measures) to lower side effects of large-scale bioenergy production without new trade-offs between the 6 sustainability indicators considered in our study. Finally, our results indicate that a combination of forest and water protection schemes, improved fertilization efficiency, and agricultural intensification would reduce side-effects of large-scale bioenergy production most comprehensively. However, our analysis also shows that more measures next to large-scale bioenergy production do not in all cases improve overall sustainability.

Our multi-criteria assessment includes a broader set of sustainability indicators than previous studies on bioenergy side-effects and their regulation. But still our study covers only a small subset of all indicators relevant for the SDG agenda. Thus, beyond the trade-offs discussed here, there are potential trade-offs with other sustainability dimensions not accounted for in our study. For instance, large-scale bioenergy crop production may have negative impacts on biodiversity as a consequence of cropland expansion or may threaten water bodies with eutrophication due to increased phosphorus fertilizer use [24, 56]. Based on that we argue that the development of policies for regulating externalities of large-scale bioenergy production should be more comprehensive. For instance, policy proposals for reducing a particular externality of large-scale bioenergy production should be subject to broad sustainability assessments to first of all discover potential trade-offs with other sustainability objectives and secondly revise policy proposals (if needed) for consistency with the SDG agenda.

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Annex 4

Humpenöder F, Popp A, Bodirsky BL, Weindl I, Biewald A, Lotze-Campen H, Dietrich JP, Klein D, Kreidenweis U, Müller C, Rolinski S, Stevanovic M (2018) Supplementary Information

Supplementary Information (SI)

Large-scale bioenergy production: How to resolve sustainability trade-offs?

by Florian Humpenöder, Alexander Popp et al.

Table of contents

1 Land-use model MAgPIE

1.1 General description

MAgPIE is a spatially explicit, global land- and water use allocation model and simulates land-use dynamics in 5-year time steps until 2100 using recursive dynamic optimization[1]. The objective function of MAgPIE is the fulfilment of food, feed, material and bioenergy demand at minimum costs under socio-economic and biophysical constraints (see Figure S1 for a schematic overview of the model).

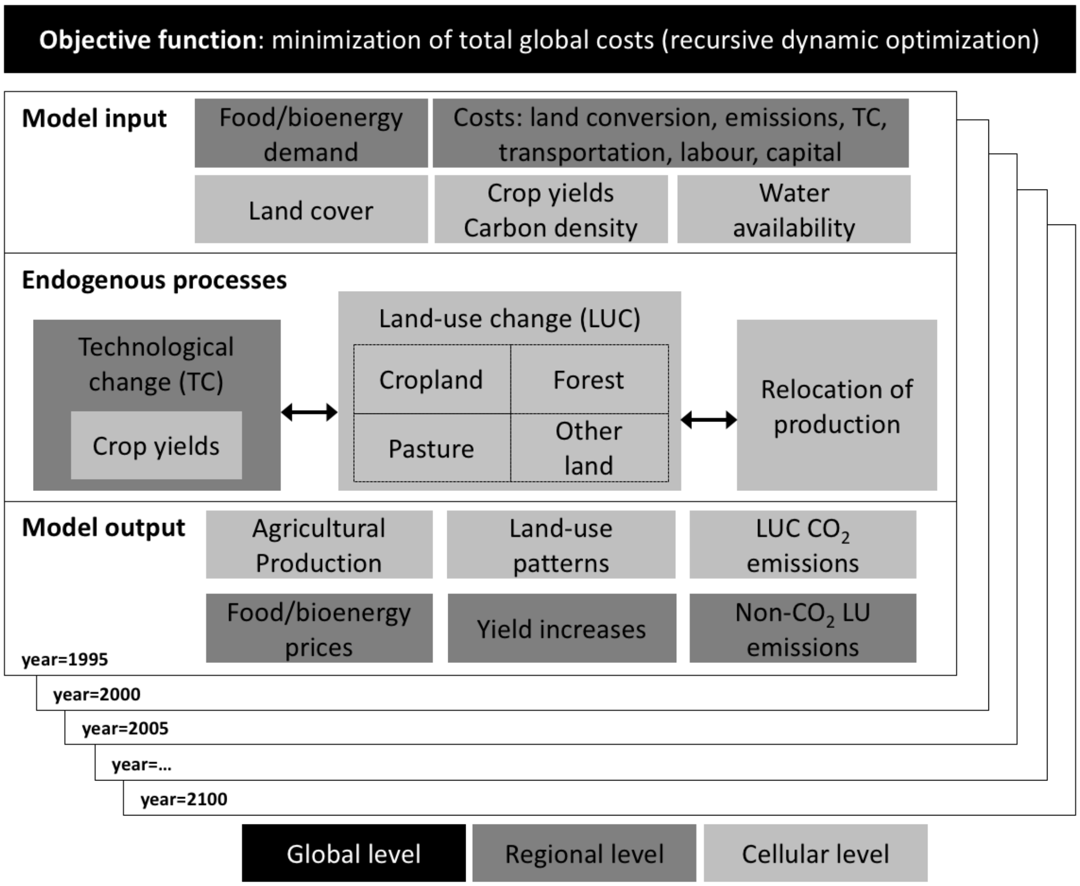


Figure S1| Schematic overview of the MAgPIE model showing (from top to bottom): objective function, key model inputs, key endogenous processes and key model outputs. Shades of grey indicate different spatial resolutions (global, regional and cellular level) for the components and processes of the model. The overlapping layers for different years (1995, 2000, 2005 ... 2100) reflect the recursive dynamic optimization approach with a time step length of 5 years.

Demand trajectories are based on exogenous future population and income projections (see Section 2, Key scenario inputs). Major cost types in MAgPIE are: factor requirement costs (capital, labour and fertilizer), land conversion costs, transportation costs to the closest market and investment costs for technological change. Socio-economic constraints like demand, factor requirement costs and investment costs are defined for 10 world regions (Figure S7, Table S2). Biophysical constraints such as crop yields, carbon density and water availability – derived from the global hydrology and vegetation model LPJmL (Lund-Potsdam-Jena model for managed Land)[2–4] – as well as land availability[5,6], are introduced at the grid cell level (0.5 degree longitude/latitude; 59,199 grid cells). Due to computational constraints, all model inputs in 0.5 degree resolution are aggregated to 700 simulation units for the optimization process based on a k-means clustering algorithm[7]. The clustering algorithm combines grid cells to simulation units based on the similarity of biophysical conditions. The cost minimization problem is solved through endogenous variation of spatial rainfed and irrigated production patterns (subject to regional trade constraints[8], land conversion (all at simulation unit level) and technological change (at regional level)[9].

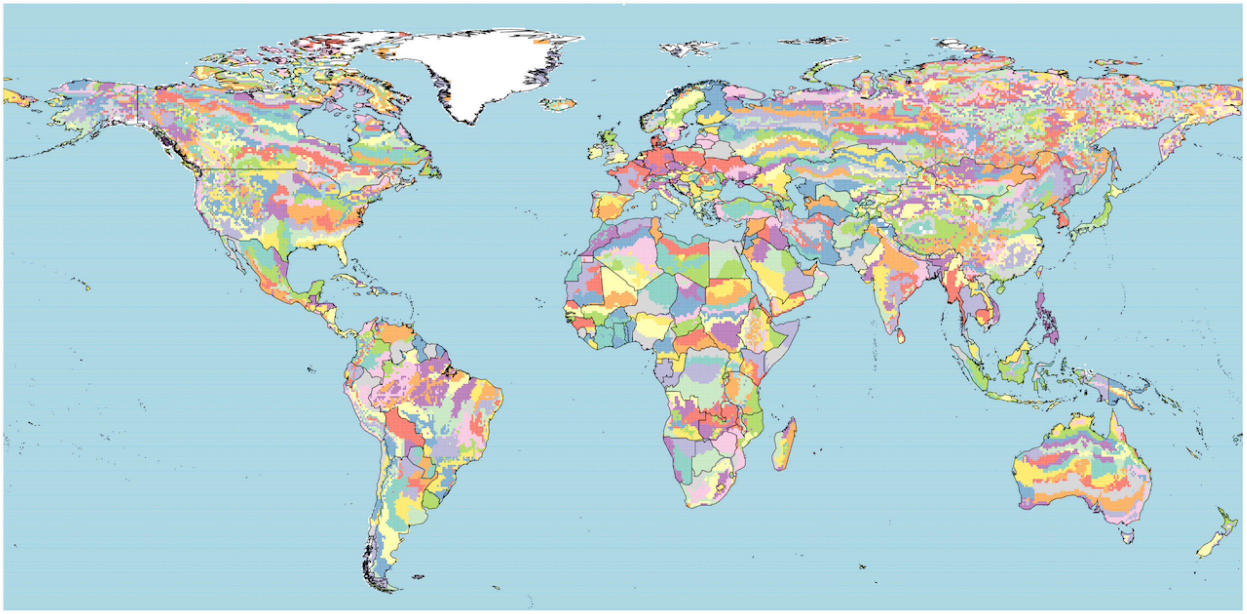


Figure S2| Spatially explicit simulation units (clusters) in MAgPIE. Due to computational constraints, all model inputs in 0.5 degree resolution are aggregated to 700 simulation units for the optimization process based on a k-means clustering algorithm[7].

MAgPIE features land-use competition based on cost-effectiveness at simulation unit level among the land-use related activities food, livestock and bioenergy production. Available land types are cropland, pasture, forest, other land (including non-forest natural vegetation, abandoned agricultural land and desert) and settlements (Figure S3). Cropland (rainfed and irrigated), pasture, forest and other land are endogenously determined, while settlement areas are assumed to be constant over time. The forestry sector, in contrast to the agricultural and livestock sectors, is currently not implemented dynamically in MAgPIE. Therefore, timberland needed for wood production - consisting of forest plantations and modified natural forest - is excluded from the optimization (about 30% of the initial global forest area). In addition, other parts of forestland, mainly undisturbed natural forest, are within protected forest areas, which cover about 12.5% of the initial global forest area[10]. Altogether, about 86% of the world's land surface is freely available in the optimization of the initial time-step.

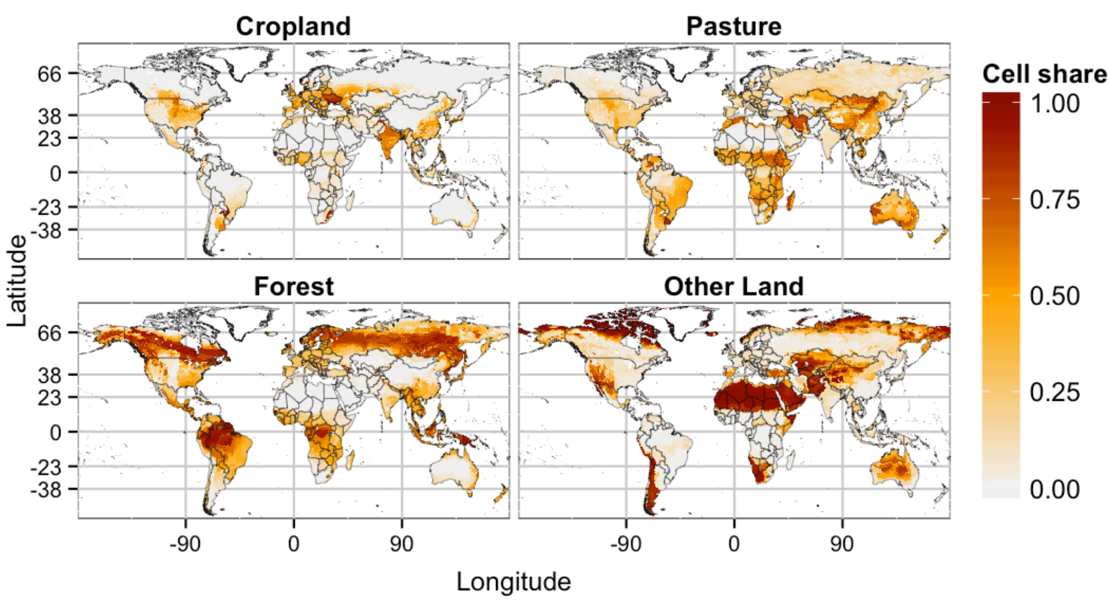


Figure S3| Spatially explicit land use / land cover used for the initialization of MAgPIE. For each grid cell, the cell shares of the four land types add up to 1. In this figure, settlements/urban area (static over time) are included in "Other Land", while in MAgPIE urban area is a separate land type.

The cropland covers cultivation of 16 food/feed crop types (e.g. temperate and tropical cereals, maize, rice, oilseeds, roots), both rainfed and irrigated systems, and two 2nd generation bioenergy crop types (grassy and woody). Biophysical yields for these crop types as well as carbon densities of natural vegetation and water availability for irrigation are derived by the dynamic global vegetation, hydrology and crop growth model LPJmL[2,3]. LPJmL simulations of crop yields assume that all crops are grown in all grid cells to assess the possible crop productivity also in areas currently not used for the cultivation of that crop to inform possible shifts in cropping areas. LPJmL crop yields reflect average annual yields, i.e. double cropping is accounted for. In seven individual LPJmL runs, crop yields are derived for seven different intensity levels. LPJmL represents potential crop yields, while MAgPIE aims to represent actual crop yields. Thus, cropping intensities are selected to match observed yields from FAO[11] at country level under the initial land-use pattern in MAgPIE. In a second calibration step, regional crop yields are adjusted to maximize agreement between MAgPIE and FAO cropland in the starting year for each of the 10 world regions (Table S1; see Figure S4 for tropical cereal yields in LPJmL and MAgPIE). In order to keep the cropping mix within plausible bounds (e.g. to account for fallow cropping) we impose rotational constraints in the cropland module of MAgPIE.

AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
0.51	0.64	0.64	0.56	0.48	0.59	0.73	0.37	0.64	0.67

Table S1: Regional crop yield calibration factors. The yield calibration factors are used for the conversion of LPJmL potential crop yields to actual yields for the initial time step of MAgPIE.

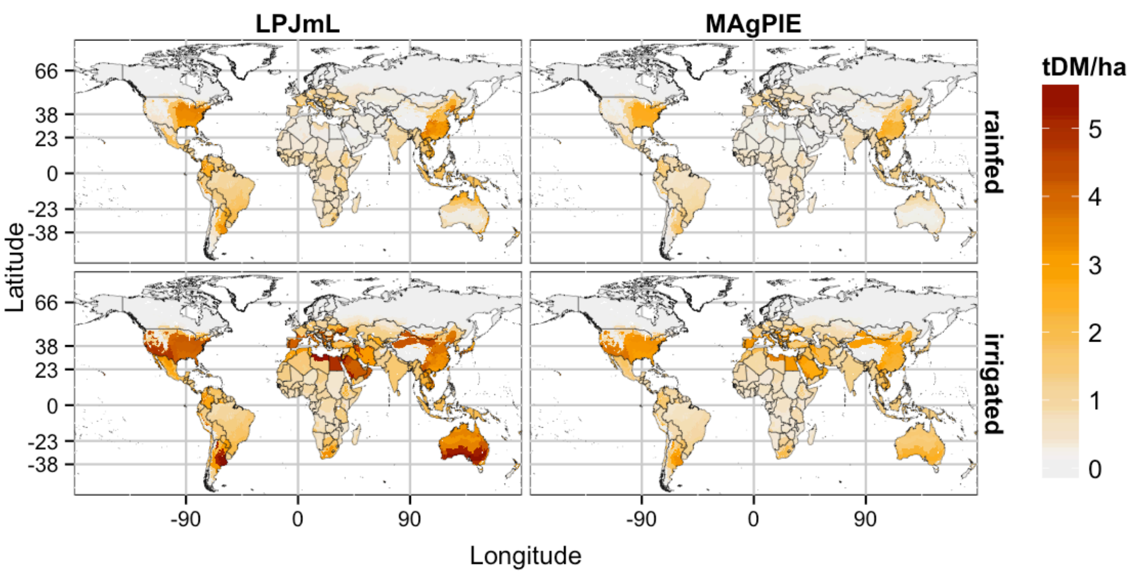


Figure S4| Tropical cereal yields in rainfed and irrigated production systems as derived by LPJmL, and how these yields are adjusted before entering MAgPIE. The calibration factors used for reducing LPJmL potential yields are shown in Table S1.

The supply of animal food commodities is divided into five livestock production activities (ruminant meat, pig meat, poultry meat, eggs and milk). The quantity of livestock production in combination with regional and livestock-specific feed baskets determines the demand for feed. Endogenous technical change in MAgPIE not only increases crop yields but also grassland yields. In contrast, livestock productivity is driven by exogenous projections (see section 3.4), and determines feed energy requirements and feed basket composition, leading to a higher share of concentrate with higher yields.

An additional LPJmL simulation assumes that all grid cells are covered with natural vegetation, which involves a spin-up period of 1000 years to bring vegetation patterns and carbon pools into equilibrium. Results from this simulation of natural vegetation are used to provide data on biophysical carbon densities (Figure S5) and water availability (Figure S6) to the MAgPIE model. The actual cell-specific carbon density in MAgPIE depends on the land allocation within each cell (calculated as area weighted mean).

Cropland and pasture carbon densities are estimated based on LPJmL and data from IPCC (Table 5.5)[12]. For forest and other land, the LPJmL information is used without modification for all carbon pools.

MAgPIE calculates carbon stocks at the cell level as the product of land-type specific area and carbon density. If, for instance, forest is converted to cropland within the same simulation unit, the carbon stock of this unit decreases according to the difference in carbon density of forest and cropland. In case agricultural land is abandoned (other land pool), ecological succession leads to regrowth of natural vegetation carbon stocks along sigmoid growth curves[13]. Regrowth of carbon stocks in MAgPIE is constrained by the LPJmL natural vegetation carbon density. If the vegetation carbon density of re-growing vegetation passes a threshold of 20 tC/ha, the respective area is shifted to the forest land pool (based on Hurtt et al[14,15]). In climate policy scenarios, mitigation of CO_2 emissions from land-use change is incentivized by an exogenous CO_2 price, which is applied on emissions from the conversion of forests and other natural land. The CO_2 price is multiplied with CO_2 emissions to calculate CO_2 emission costs, which enter the cost-minimizing objective function of MAgPIE.

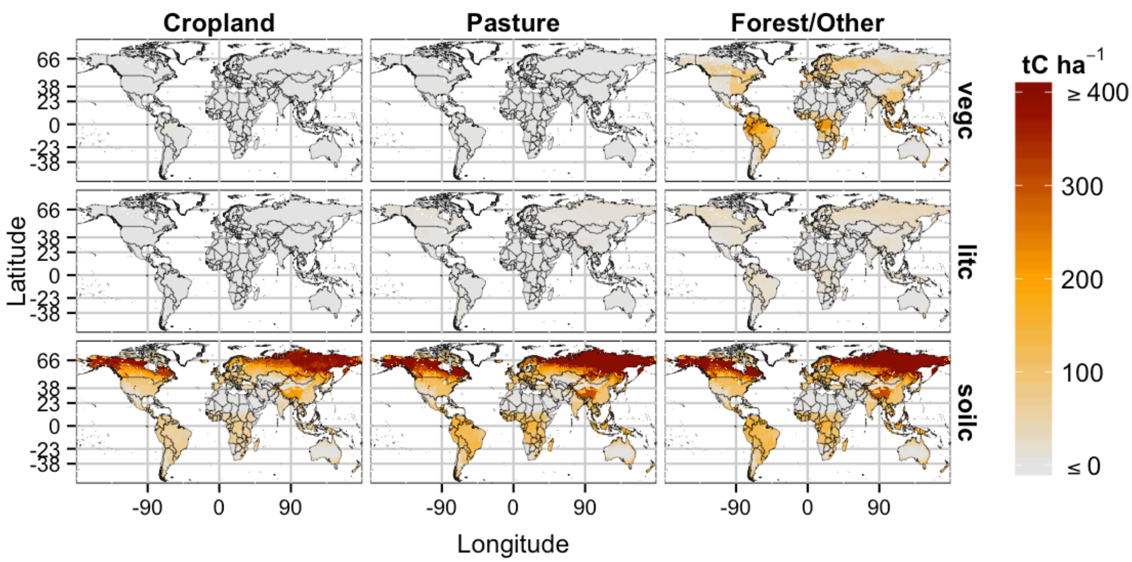


Figure S5| Spatially explicit carbon density (tC ha^{-1}) based on LPJmL for four land types and the three carbon pools vegetation, litter and soil (vegc, litc, soilc).

In MAgPIE, available water at simulation unit level for domestic, industrial and agricultural use comprises renewable blue water resources only, i.e. precipitation that enters rivers, lakes and aquifers[16]. Input data for available water is obtained from LPJmL (Figure S6). By default, we assume that all renewable freshwater is available for human use, i.e. no water is reserved for environmental purposes. Domestic and industrial water demand enters the model as an exogenous scenario based on WaterGAP simulations[17,18]. We assume that domestic and industrial water demand is fulfilled first, effectively limiting water availability for agricultural use (similar to Elliott et al[19]). Within these limits of available water, agricultural water demand for irrigated food, feed and bioenergy production as well as livestock feeding is determined endogenously based on cost-effectiveness. Spatially explicit per hectare irrigation water requirements for the 16 food crops and 2 bioenergy crops represented in MAgPIE are obtained from LPJmL. Rainfed crop production relies on green water resources only, i.e. precipitation infiltrated into the soil, and does therefore not affect agricultural irrigation water demand.
Irrigated crop production is not only constrained by water availability, but also requires irrigation infrastructure for water distribution and application. The initial pattern of area equipped for irrigation is taken from the AQUASTAT database (Siebert et al[20]). During the optimization process, the model can endogenously deploy additional irrigation infrastructure[21].

Since MAgPIE is an economic optimization model operating under constrained conditions, it is possible to generate a shadow price for every independent constraint (e.g. the food or bioenergy demand constraint)[21]. In economic terms, the shadow price reflects the decrease of costs in the objective function if one additional unit of output would be available. In other words, shadow prices reflect the marginal increase in production costs for one additional unit of output.

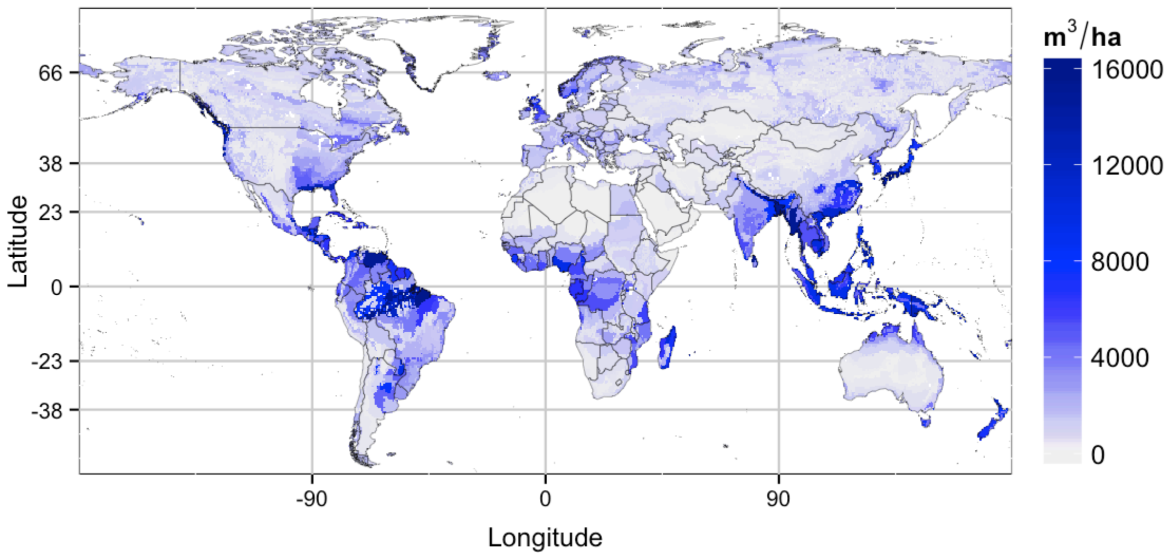


Figure S6| Available water for irrigation in MAgPIE, derived from LPJmL[2,3] (same as in Bonsch et al.[22])

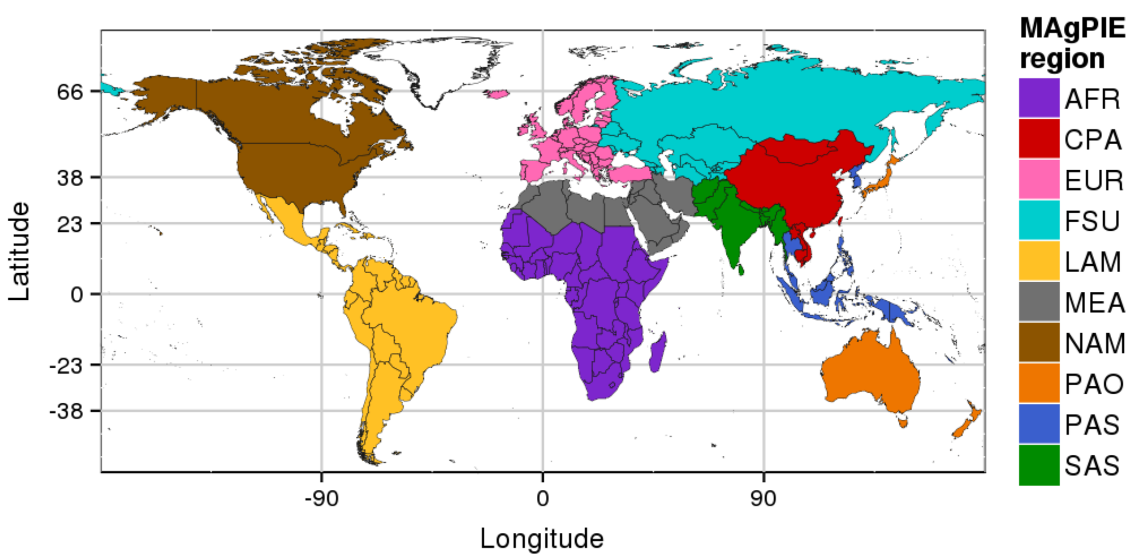


Figure S7| MAgPIE economic world regions

MAgPIE	Region
AFR	Sub-Saharan Africa
CPA	Centrally planned Asia including China
EUR	Europe including Turkey
FSU	States of the former Soviet Union
LAM	Latin America
MEA	Middle East/North Africa
NAM	North America
PAO	Pacific OECD including Japan, Australia, New Zealand
PAS	Pacific (or Southeast) Asia
SAS	South Asia including India

Table S2| Abbreviations and names of the 10 economic world regions in MAgPIE

1.2 Bioenergy

Present day bioenergy production relies mainly on conventional food crops such as maize and sugarcane (1st generation bioenergy). In order to avoid competition with food production, techniques are being developed to convert the lignocellulosic components of plant biomass to biofuels[23,24]. This will allow the use of dedicated grassy and woody bioenergy crops (2nd generation bioenergy) and is expected to increase the energy yield per unit of crop significantly[23].

MAgPIE simulates both 1st and 2nd generation bioenergy crop production. 1st generation bioenergy production is based on food crops, while 2nd generation bioenergy production is based on dedicated herbaceous and woody lignocellulosic bioenergy crops. Demand for 1st generation bioenergy is defined at the regional level (10 world regions) based on currently existing 1st generation biofuel polices (see section 2.2). In contrast, demand for 2nd generation bioenergy, in this study, enters the model at the global level based on projections from Integrated Assessment Models (IAMs) for bioenergy deployment in 1.5°C and 2°C transformation pathways (see section 2.2). Since the focus of this study is on 2nd generation bioenergy we provide more details for 2nd generation bioenergy in the remainder of this subsection.

2nd generation bioenergy crop production in MAgPIE is subject to the same constraints that apply to all other food/feed crop production activities, i.e. there are no special rules for bioenergy crop production. Crucial factors influencing bioenergy crop production patterns in MAgPIE are land availability, attainable yields (sub-section 1.2.1) and production costs. The spatial allocation of 2nd generation bioenergy crop production is an endogenous model decision resulting from the cost minimizing objective function, which takes into account land and water availability as well as bioenergy yields and production costs.

Within the boundaries of the model, there are several options to fulfil increasing 2nd generation bioenergy demand. One of these options is cropland expansion into forest or other natural land. In general, all land types in MAgPIE (cropland, pasture, forest and other land; Figure S3) are available for land conversion in each grid-cell (e.g. forest-to-cropland or pasture-to-cropland). About 42.5% of the initial global forest area in MAgPIE is excluded from the land available for conversion to account for wood production and forest protection (see section 1.1). For instance, bioenergy crop production can expand into forest areas. Cropland expansion into forests, however, is limited by accounting for intra-regional transport costs in the objective function. Intra-regional transport costs are based on the GTAP 7 database[25] and a global map of accessibility[26] (travel time to major cities; http://forobs.jrc.ec.europa.eu/products/gam/). An additional (scenario-depended) factor limiting cropland expansion into forests is a price on CO_2 emissions from deforestation. In that case, an additional term enters the cost-minimizing objective function.

Another option to fulfil 2nd generation bioenergy demand in MAgPIE is to expand bioenergy crop production into areas currently used for agricultural production (cropland and pasture). We assume competition for land among all land demanding activities in MAgPIE (including food and bioenergy crop production) based on the underlying cost-minimization approach. This implies that food crop production can be displaced within a region or to another region by bioenergy crop production. At the global level, however, food crop production remains constant because regionally prescribed food demand ensures that food crop production is expanded elsewhere, potentially associated with additional deforestation. Displacement of food production to other regions involves trade and is limited by self-sufficiency rates. There are two trade pools in the model, one with trade according to historical trade patterns (self-sufficiency rates), and another one with free trade according to comparative advantages. Reducing trade barriers increases the free trade pool. In our SSP2 scenario, agricultural trade barriers decline by 0.5% per year.

Besides land expansion, yield increases of bioenergy as well as food crops contribute to the fulfilment of 2nd generation bioenergy demand in MAgPIE. Technological change (see sub-section 3.4 for details) and irrigation can directly increase crop yields in MAgPIE, besides indirect crop yield improvement through changes in spatial production patterns (partly limited by trade restrictions). Technological change in MAgPIE leads not only to yield increases but also to increases in agricultural land-use intensity, which in turn raises costs for further yield increases. Irrigated bioenergy crop production results in substantially higher yields per unit area compared to rainfed bioenergy crop production (Table S3, Figure S8). But irrigated bioenergy crop production is more expensive compared to rainfed bioenergy crop production because of higher costs for infrastructure, operation and maintenance. Based on the GTAP 7 database[25], we assume factor requirement costs of 230 US$04 per ton DM for rainfed and 310 US$04 per ton DM for irrigated bioenergy crop production. In addition, irrigation infrastructure, which is needed for irrigation, can be expanded at additional costs[27]. Irrigation in MAgPIE is limited by water availability (Figure S6).

1.2.1 Yields

In MAgPIE, 2nd generation bioenergy crops can be grown in rainfed and irrigated production systems. Rainfed and irrigated bioenergy yields at simulation unit level for the initialization of MAgPIE are derived from LPJmL[28]. While LPJmL simulations supply data on potential yields, i.e. yields achieved under the best currently available management options, MAgPIE aims to represent actual yields. Therefore, LPJmL bioenergy yields are calibrated using information on observed cropland area from FAO[11] and observed land-use intensity from Dietrich et al[29] to arrive at actual yields. The goal of the yield calibration is to maximize agreement of total cropland in MAgPIE with FAO data at regional level in 1995[11]. As there is currently no robust information on 2nd generation bioenergy available in FAO[11], observed land-use intensity from Dietrich et al[29] is used as additional factor for the calibration of bioenergy yields in MAgPIE. LPJmL potential bioenergy yields are consistent with observations from well managed test sites in Europe and the USA[28]. Therefore, it is assumed that LPJmL bioenergy yields agree with yields achieved under highest currently observed land use intensification (which agrees with the values in EUR, Figure 2 in Dietrich et al[29]). Bioenergy yields in all other regions are downscaled proportional to the land use intensity of EUR. Low calibration factors for Sub-Saharan Africa (0.26) and Latin America (0.36) reflect large yield gaps with respect to best management practices (Table S3).

	GLO	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
woody rainfed	50	28	55	58	19	69	3	45	12	166	41
woody irrigated	160	219	143	111	61	164	218	99	151	204	228
herbaceous rainfed	125	103	143	93	37	207	14	90	44	394	125
herbaceous irrigated	341	488	270	167	97	371	531	160	333	456	534
calibration factors	-	0.26	0.55	0.64	0.34	0.36	0.29	0.66	0.23	0.42	0.43

Table S3: Global and regional average actual bioenergy yields (GJ/ha) in the initial time step of MAgPIE. The average is obtained by calculating the non-weighted mean yield over all simulation units in a specific region, irrespective of whether bioenergy is actually grown. Bioenergy yields are derived from LPJmL potential yields[28] and calibrated using information on observed cropland area[11] and observed land-use intensity[29] to arrive at actual yields. Regional calibration factors are shown in the bottom row.

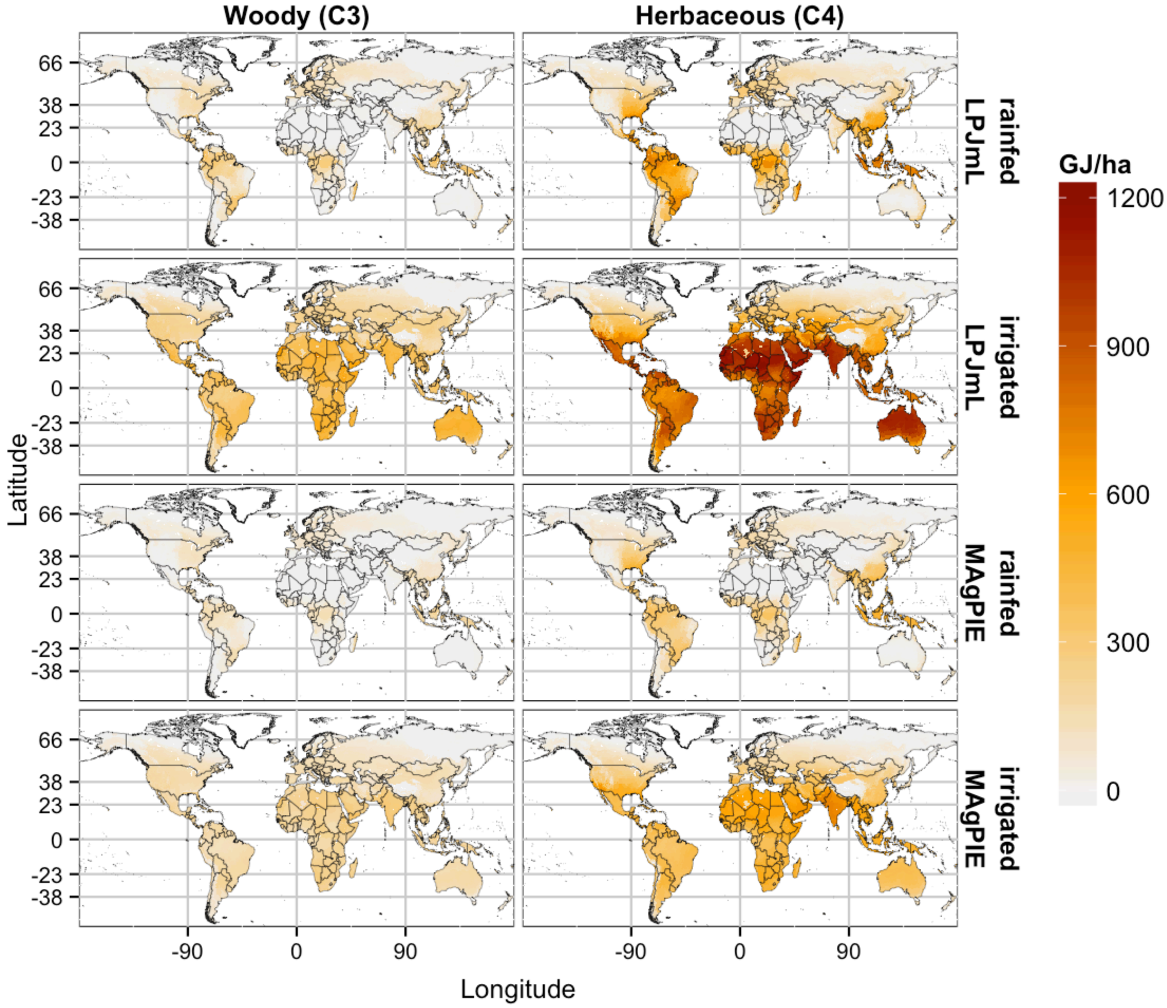


Figure S8| Woody and herbaceous bioenergy crop yields in rainfed and irrigated production systems as derived by LPJmL[28], and how these yields are adjusted before entering MAgPIE. LPJmL represents potential yields, while MAgPIE aims to represent actual yields. The calibration factors used for reducing LPJmL potential yields are shown in Table S3. The gross energy content of bioenergy is assumed 18 GJ per ton DM[30].

2 Key scenario inputs

2.1 Food demand (SSP1, SSP2, SSP5)

Food demand in MAgPIE for 10 world regions is calculated based on population and income projections for the 21st century from the Shared Socio-economic Pathways (SSP) database[31,32]. The methodology for calculating food demand (time-dependent regression models between calorie demand and income) is described in detail in Bodirski et al[33]. In this study, we use SSP1, SSP2 and SSP5 population and income projections to derive food demand scenarios. In a first step, we use the SSP income projections (Figure S10) to derive per-capita food demand (Figure S11) using the methodology described in Bodirski et al[33]. In a second step, we multiply per-capita food demand (Figure S11) with population (Figure S9) to calculate total food demand (Figure S12), which is subsequently used as input for MAgPIE.

In this study, we use the SSP2 (middle-of-the-road) food demand scenario as default setting. SSP1 (sustainable development) and SSP5 (fossil-fueled development) are used for sensitivity analysis. SSP1 and SSP5 have similar population dynamics (Figure S9) but very different income dynamics (Figure S10). Income in SSP5 is growing much faster compared to SSP1 (and SSP2), which results in higher per-capita food demand (Figure S11). Consequently, total food demand is increasing from SSP1, to SSP2 to SSP5 (Figure S12).

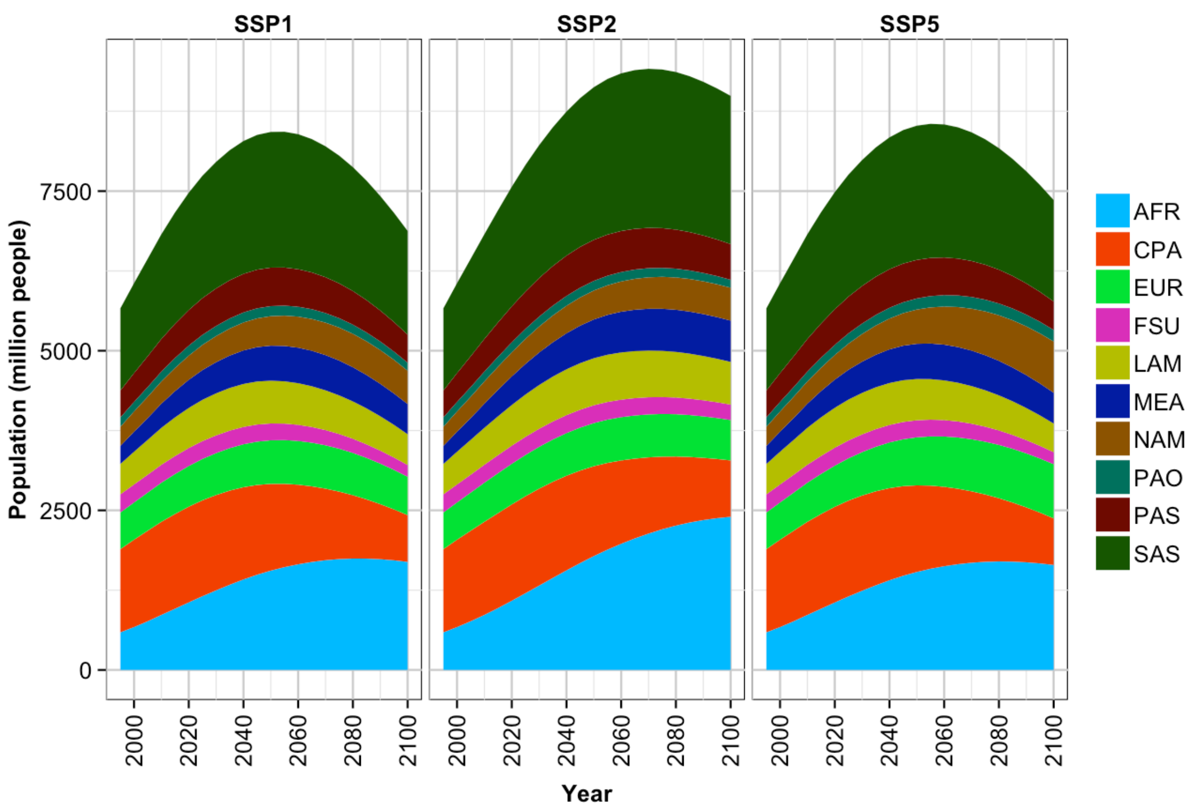


Figure S9| Population projections for the scenarios SSP1, SSP2 and SSP5 taken from the SSP database[31].

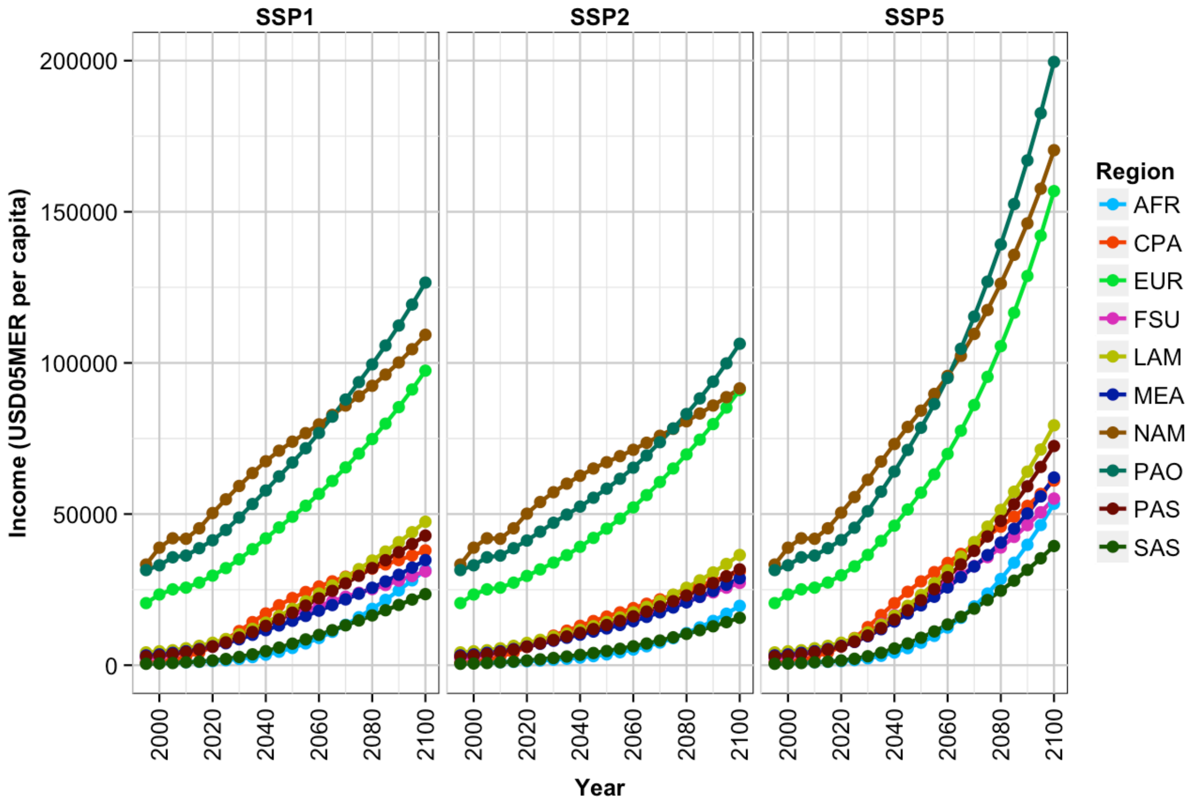


Figure S10| Income projections for the scenarios SSP1, SSP2 and SSP5 taken from the SSP database[31].

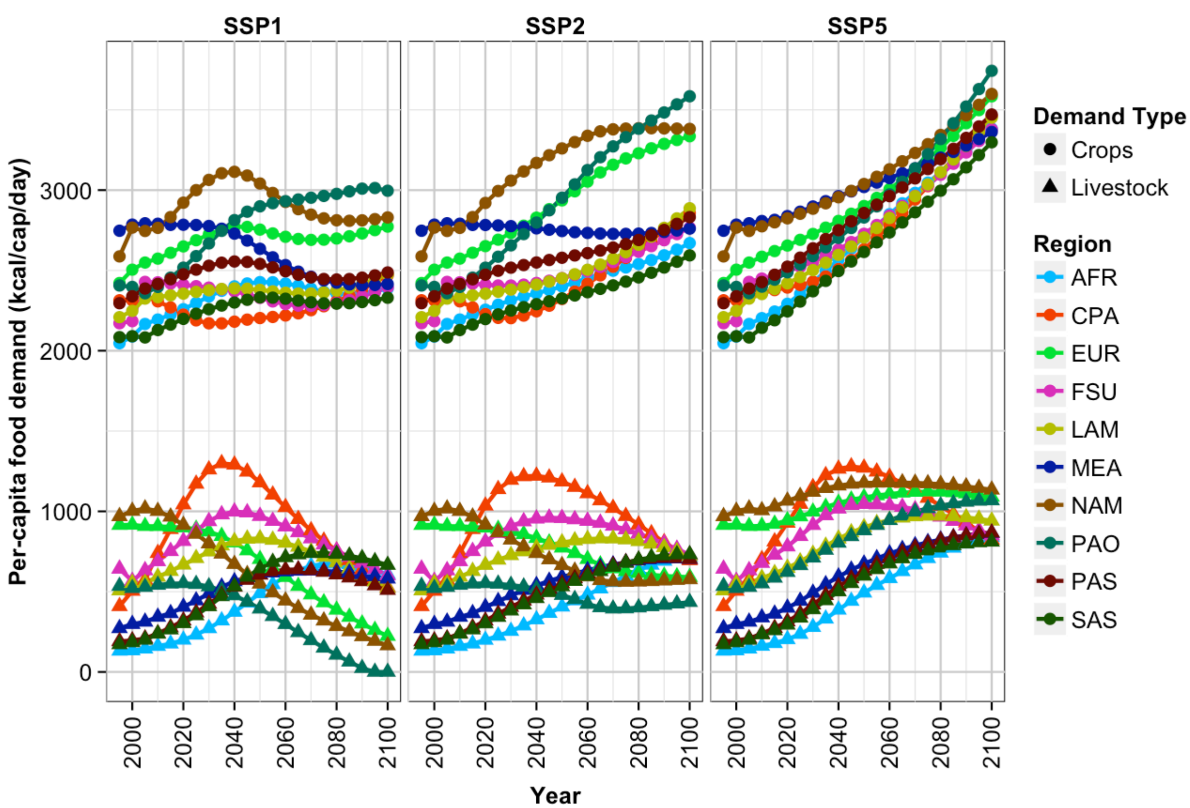


Figure S11| Per-capita food demand for the scenarios SSP1, SSP2 and SSP5 calculated using the methodology described in Bodirski et al[33].

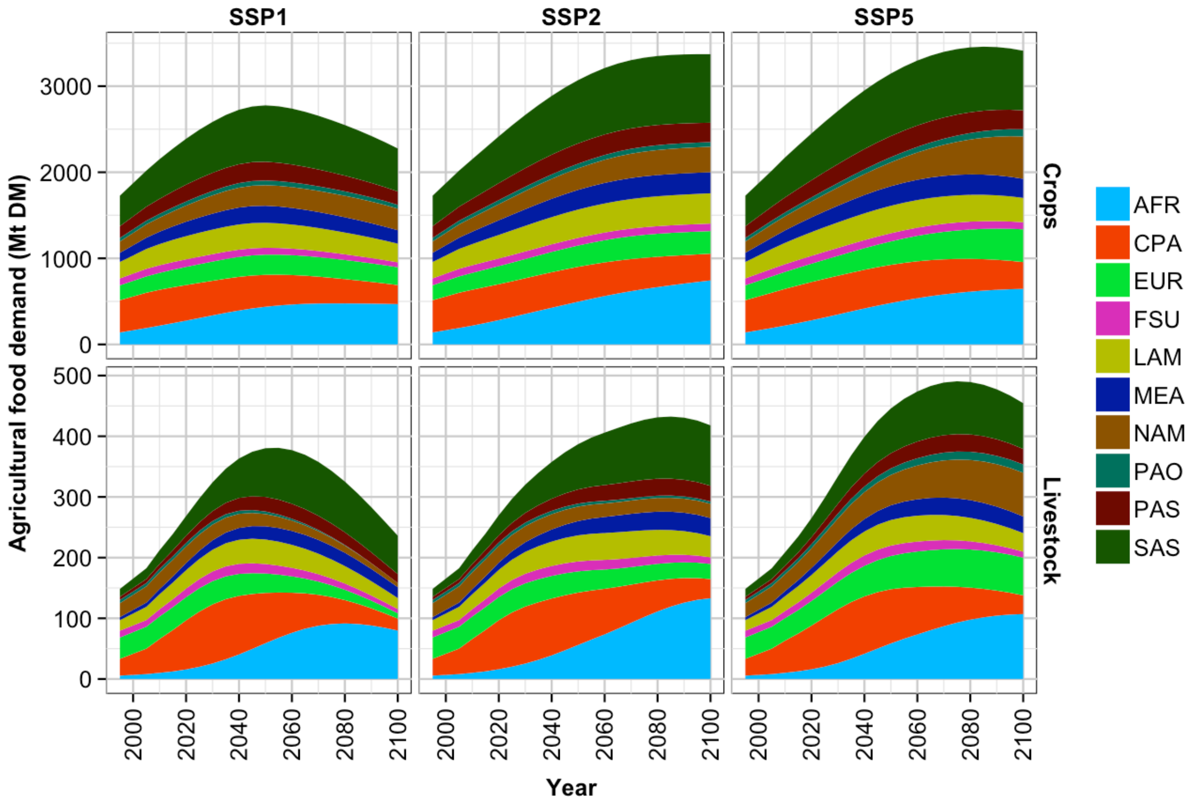


Figure S12| Total food demand (crops and livestock products) for the scenarios SSP1, SSP2 and SSP5.

2.2 Bioenergy demand (1st and 2nd generation)

1st generation bioenergy

We assume identical 1st generation bioenergy demand across all scenarios analysed in this study. 1st generation bioenergy demand is taken from the SSP database (REMIND-MAgPIE SSP2-Ref scenario)[31]. The demand trajectory for 10 world regions, which is based on current 1st generation biofuel polices, increases to about 7 EJ globally by 2020 and remains constant thereafter (Figure S13).

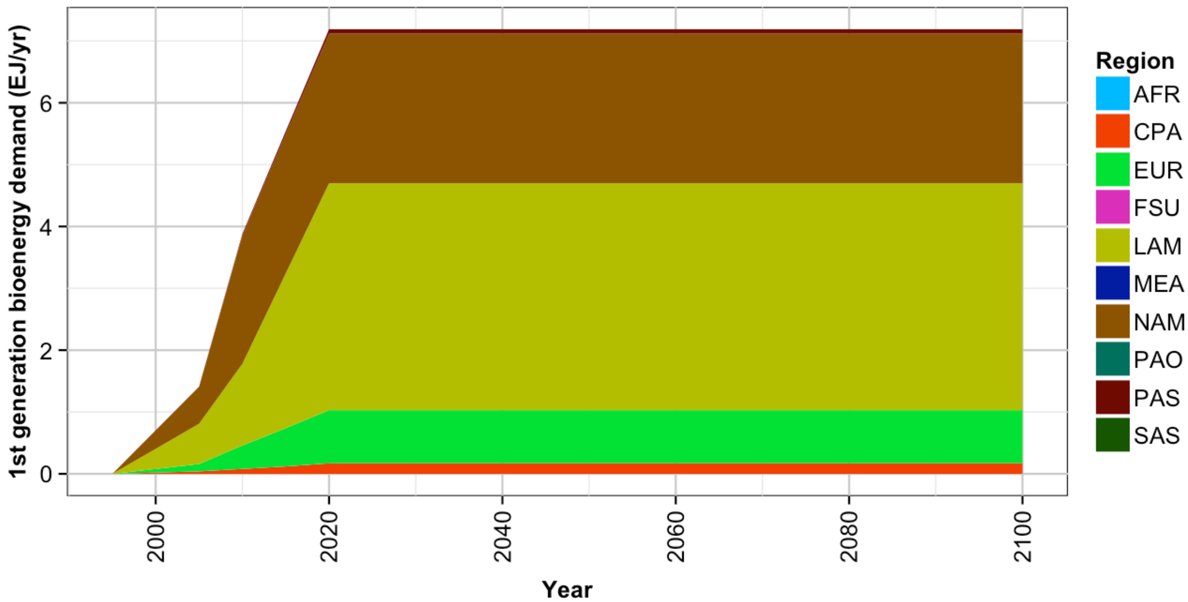


Figure S13| 1st generation bioenergy demand assumed in all MAgPIE scenarios.

2nd generation bioenergy

For 2nd generation bioenergy, we analyse two demand scenarios (Figure S14): no demand at all (*NoBio*) and a linear increase in demand from 0 EJ/yr in 2010 to 300 EJ/yr in 2100 globally (*Bio*). 2nd generation bioenergy demand of up to 300 EJ in year 2100 reflects the upper end of projections from Integrated Assessment Models (IAMs) for bioenergy deployment in 1.5°C and 2°C transformation pathways[34].

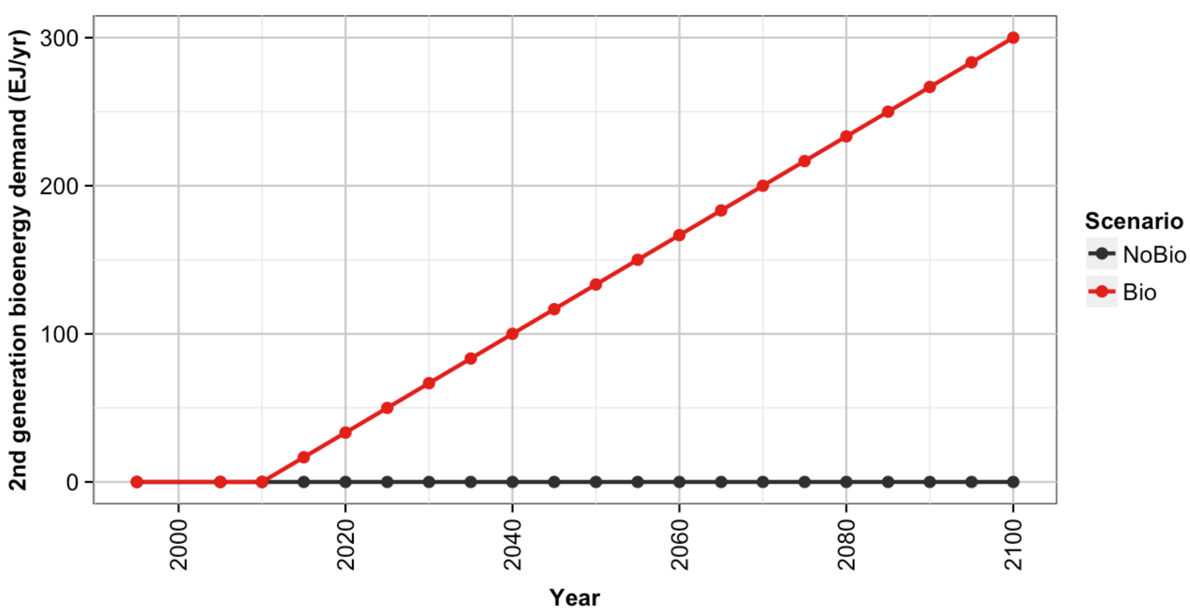


Figure S14| 2nd generation bioenergy demand scenarios defined at the global level.

3 Scenario implementations

The scenario analysis presented in this study builds on previous work with the MAgPIE model. All scenario implementations we use here in combination with large-scale 2nd generation bioenergy demand (Bio scenario, Figure S14) have been published earlier in peer-reviewed journals. In the following we describe the main characteristics of the scenario implementations and refer to peer-reviewed literature for more details.

3.1 REDD

The *REDD* scenario is a forest protection scenario, which is implemented by pricing CO_2 emissions from the conversion of forests and other natural ecosystems (same as in Popp et al[1]). The resulting costs for CO_2 emissions from land-use change enter the cost-minimizing objective function of MAgPIE. Consequently, the model tries to avoid the costly conversion of forest and other carbon-rich ecosystems. The global CO_2 price trajectory in the *REDD* scenario starts in 2015, has a level of 30 US$ per tCO_2 in 2020 and increases nonlinearly at a rate of 5% per year (same as in Popp et al[1]). In scenarios without forest protection (*Default* setting) the CO_2 price is set to 0 US$.

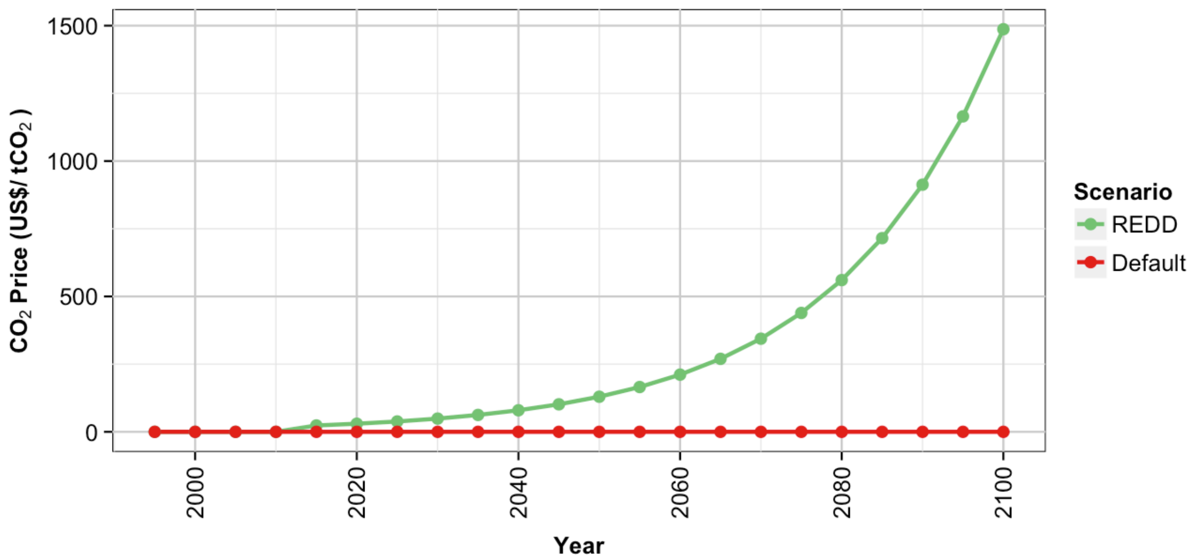


Figure S15| Global CO_2 price trajectory (same as in Popp et al[1]) applied on CO_2 emissions from the conversion of forests and other natural ecosystems.

3.2 EffNfert

The scenario *EffNfert* (efficient N fertilization) estimates effects of higher Soil Nitrogen Uptake Efficiency (SNUPE). The implementation is based on the scenario "Efficient fertilization" in Bodirsky et al[35]. The *Default* setting is identical to the "Reference (SSP2)" scenario in Bodirsky et al[35]

As the development of future soil nitrogen uptake efficiency is subject to large uncertainty, it is implemented as scenario parameter in MAgPIE. In the past, nitrogen use efficiency at the global scale has been almost constant around 50%, however with underlying regional differences. In expanding agricultural markets like India and China, nitrogen use efficiency has been falling before stabilizing in recent decades. In contrast, in high-income countries, it has been increasing. In particular in the European Union, strong improvements have been achieved since the 1990s[36,37]. This can be attributed largely to the implementation of policies like the nitrate directive which support good practice in farming. Even though with still weak empirical foundations, an environmental Kuznets-Curve reflects the development of nitrogen use efficiency in many countries, such that nitrogen use efficiency increases with socio-economic development[38]. Our scenarios follow this assumption, assuming that nitrogen use efficiency will increase in SSP2 to 60%, yet for simplicity without regional differentiation (Figure S16). For our improved management scenario *EffNfert*, we assume that nitrogen use efficiency will increases to 75% in 2050 and 85% in 2100, which is according to the EU nitrogen expert panel on the upper end of the desirable range (50-90%) that can be achieved without mining the soil organic matter of soils[39].

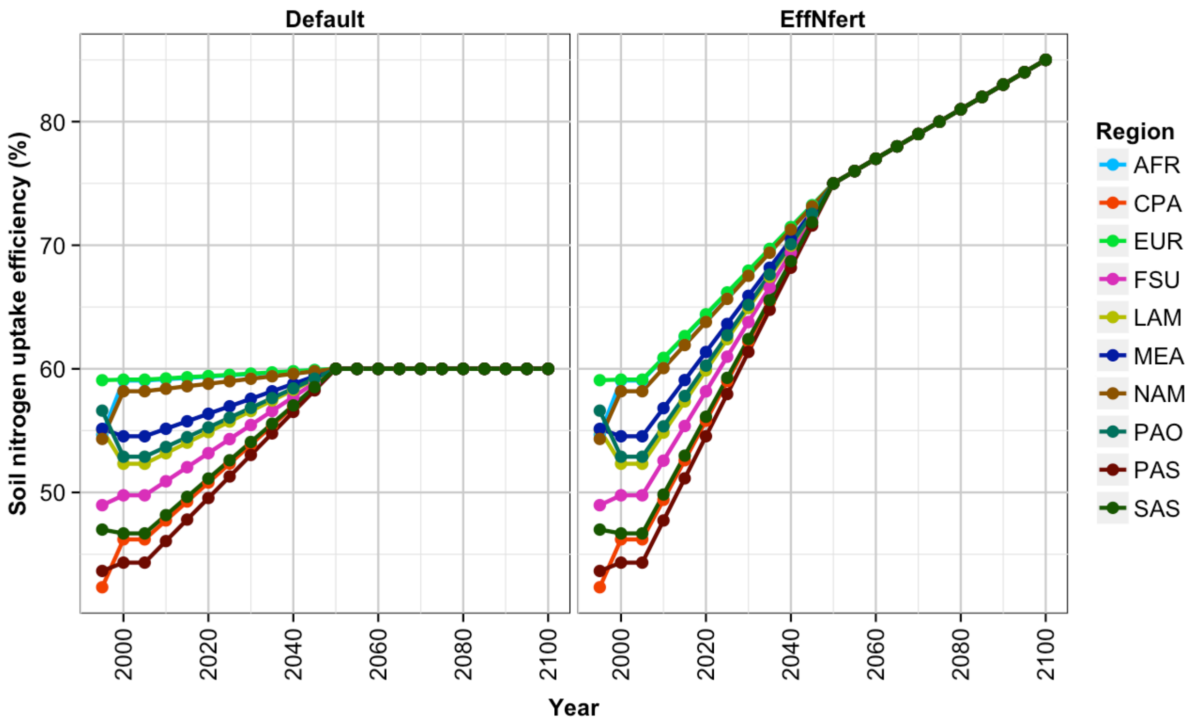


Figure S16| Soil nitrogen uptake efficiency scenarios based on Bodirsky et al[35]. In the *Default* setting, soil nitrogen uptake efficiency converges to 60% globally by 2050, and remains constant thereafter (based on the *SSP2 reference* scenario in Bodirsky et al[35]). In the *EffNfert* scenario soil nitrogen uptake efficiency converges to 75% globally by 2050, and rises to 85% by 2100 (based on the *SSP2 mitigation* scenario in Bodirsky et al[35]). The global average soil nitrogen uptake efficiency in 2010 is 53%.

3.3 WaterProt

WaterProt is a water protection scenario based on environmental flow protection (EFP). The grid-cell specific implementation is identical to the second EFP scenario (Smakhtin) in Bonsch et al[22].

In the *WaterProt* scenario, annual volumes of water are secured for environmental flow protection from 2015 onwards. In the *Default* setting there is no water allocation for EFP throughout the simulation period. The baseline assumption is based on findings that EF violation is a widespread global phenomenon. Hoekstra et al[40] have found that in 223 of 405 large river basins, EFs are violated at least one month per year. Furthermore it has been highlighted that current real-world water management rarely accounts for environmental water requirements[41,42].

The EFP scenario we use in this study relies on research by Smakhtin[43]. They propose a combination of low-flow (LFR) and high-flow (HFR) requirements to sustain river ecosystems in a “fair” condition. The conservation goal is to limit species loss to very sensitive species and to limit intrusion by alien species. LFR correspond to the 90% quantile of annual flow (Q90), i.e. to the discharge that is exceeded in nine out of ten months. Variable rivers are characterized by low Q90 values. In such cases high-flow events are important for river channel maintenance, wetland flooding, and riparian vegetation. HFR of 20% of available water are therefore assigned to rivers with a low fraction of Q90 in total discharge. Rivers with a more stable flow regime receive a lower HFR. For calculation details see Appendix A3 in Bonsch et al[22].

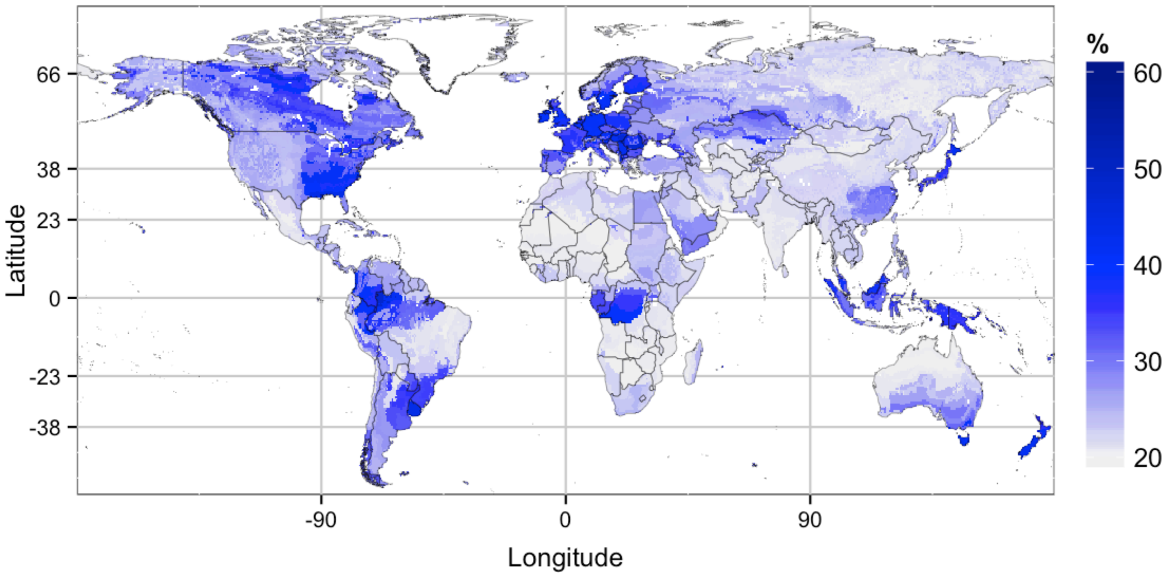


Figure S17| Grid-cell specific share of available irrigation water reserved for environmental flows in the *Bio-WaterProt* scenario, based on Bonsch et al[22]. First, environmental flow requirements (in million km^3 per year) for each grid-cell are derived using an algorithm developed by Smakhtin et al[44]. Subsequently, environmental flow requirements are divided by the available irrigation water (Figure S6) at the grid-cell level.

3.4 IntensAg

The scenario *IntensAg* (intensive agriculture) estimates effects of higher yields and higher livestock productivity.

Higher yields in *IntensAg* are the result of endogenous R&D investments in yield-increasing technological change (TC). The implementation, which is based on the effectiveness of R&D investments on yield changes (investment–yield ratio), is described in Dietrich et al[45]. Investing in TC leads not only to yield increases but also to increases in agricultural land-use intensity, which in turn raises costs for further yield increases. TC in MAgPIE increases all crop yields (including food, feed and bioenergy crops). In the *Default* setting, we fix the technological change trajectory to the level observed in the *NoBio* scenario.

Livestock productivity scenarios in MAgPIE are based on the SSP storylines for the land-use sector[32,46]. In the *IntensAg* scenario, we assume strong intensification of livestock production (based on SSP1/SSP5). Our *Default* setting is medium intensification (based on SSP2). Besides the SSP storylines, we take into account past productivity improvements, GDP projections and cultural particularities to derive future scenarios of livestock productivity (Figure S19).

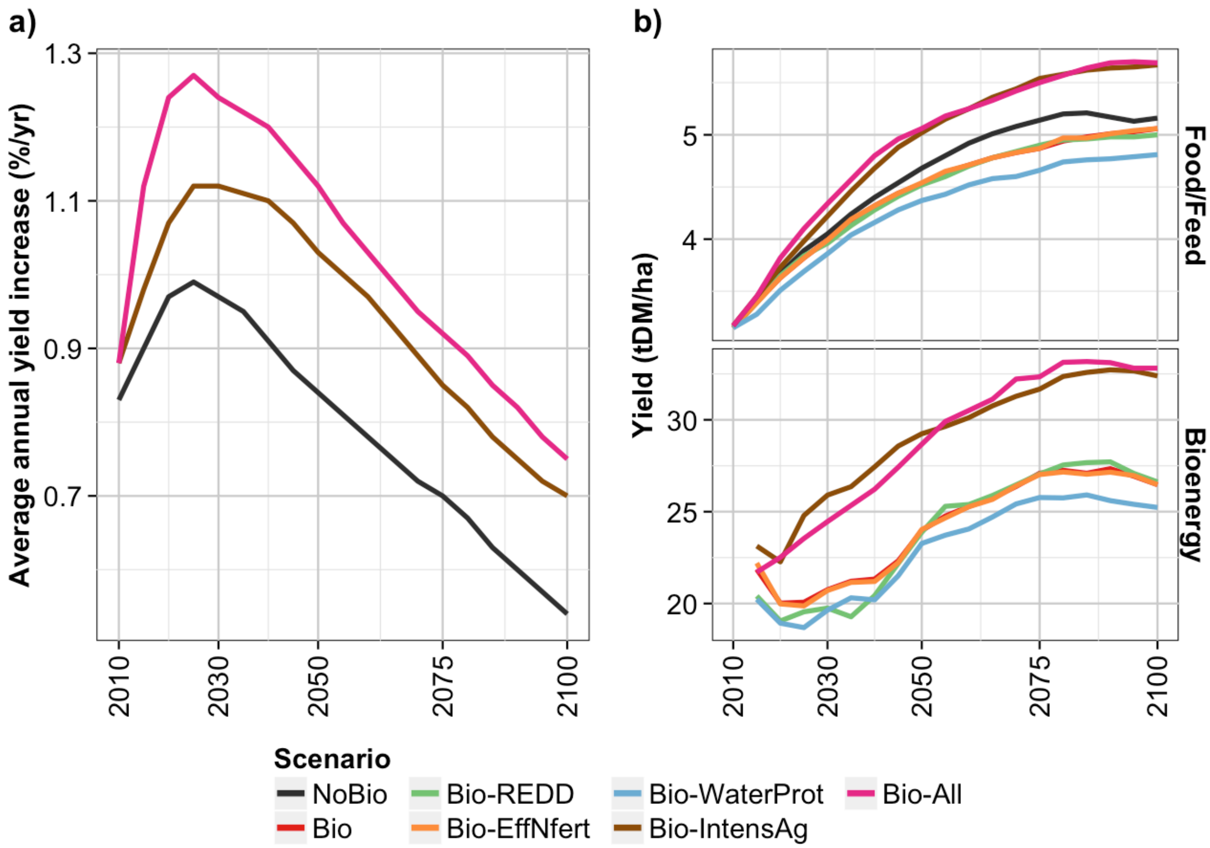


Figure S18| Time-series of global scenario results for a) crop yield increase induced by technological change, and b) absolute food/feed and bioenergy crop yields. Left panel: Average annual yield-increasing technological change in the scenarios *Bio*, *Bio-REDD*, *Bio-EffNfert, Bio-WaterProt* and is identical to *NoBio scenario* by assumption (see Table 2). In the *Bio-IntensAg* and the *Bio-All* scenario, the model has an additional degree of freedom because it can, based on a cost-minimization procedure taking into account the costs of alternatives such as land expansion, endogenously adjust investments in yield-increasing technological change. Right panel: Absolute crop yields reflect the combined effects of improved agricultural productivity, spatial allocation and irrigation.

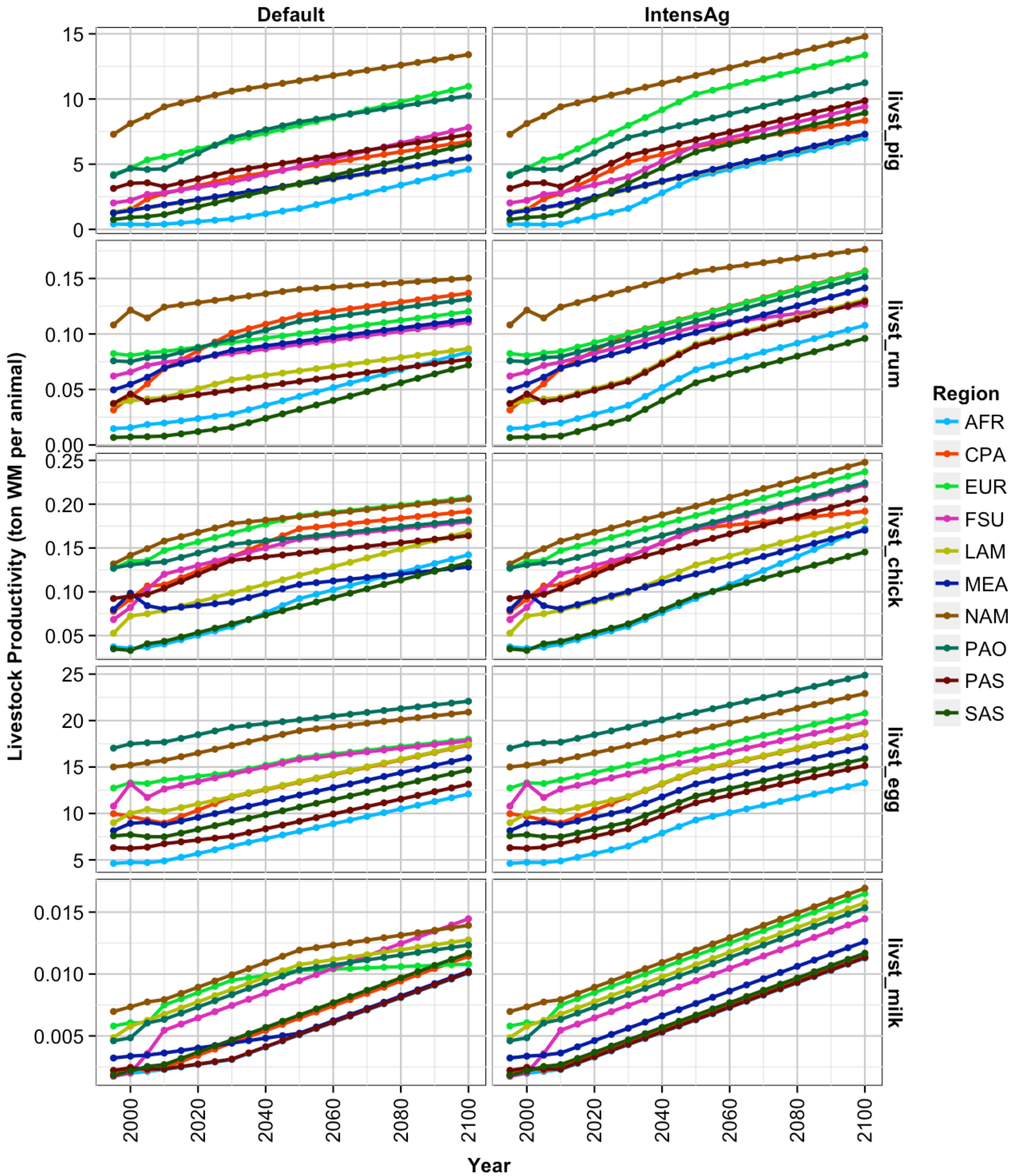


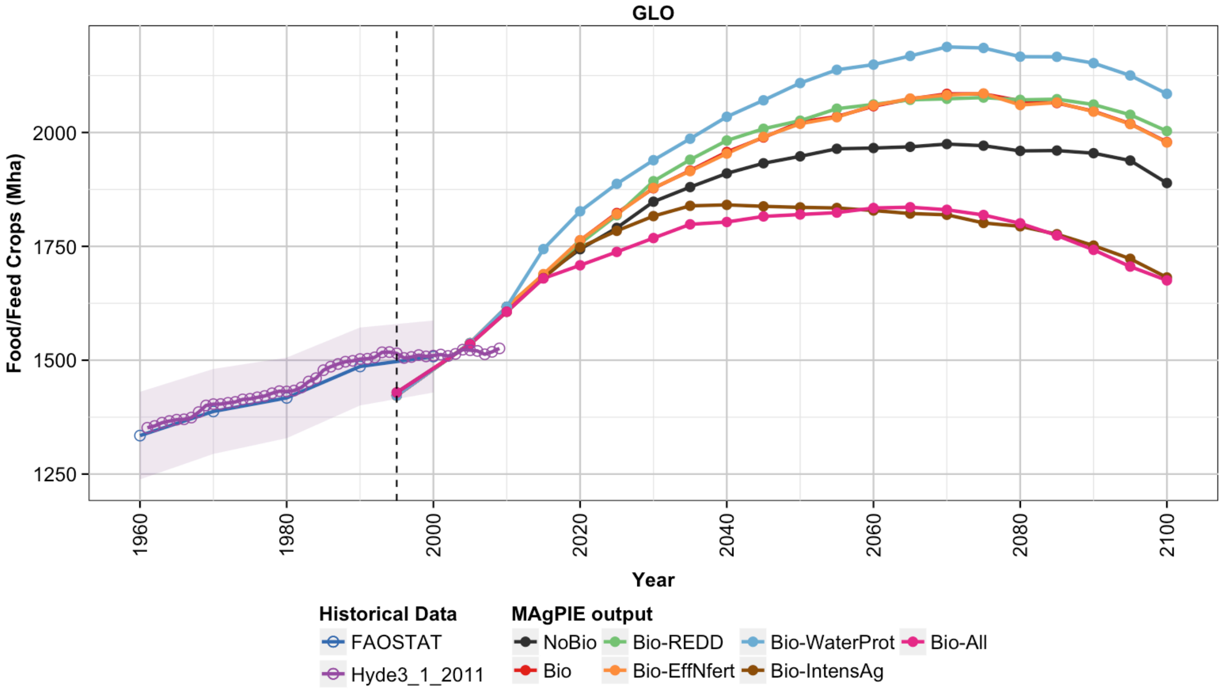
Figure S19| Livestock productivity scenarios based on SSP story lines. *Default* is based on SSP2 (medium intensification), *IntensAg* is based on SSP1/SSP5 (strong intensification).

4 Validation of scenario results

Validation of agricultural, environmental and socio-economic indicators

4.1 Cropland

a)



b)

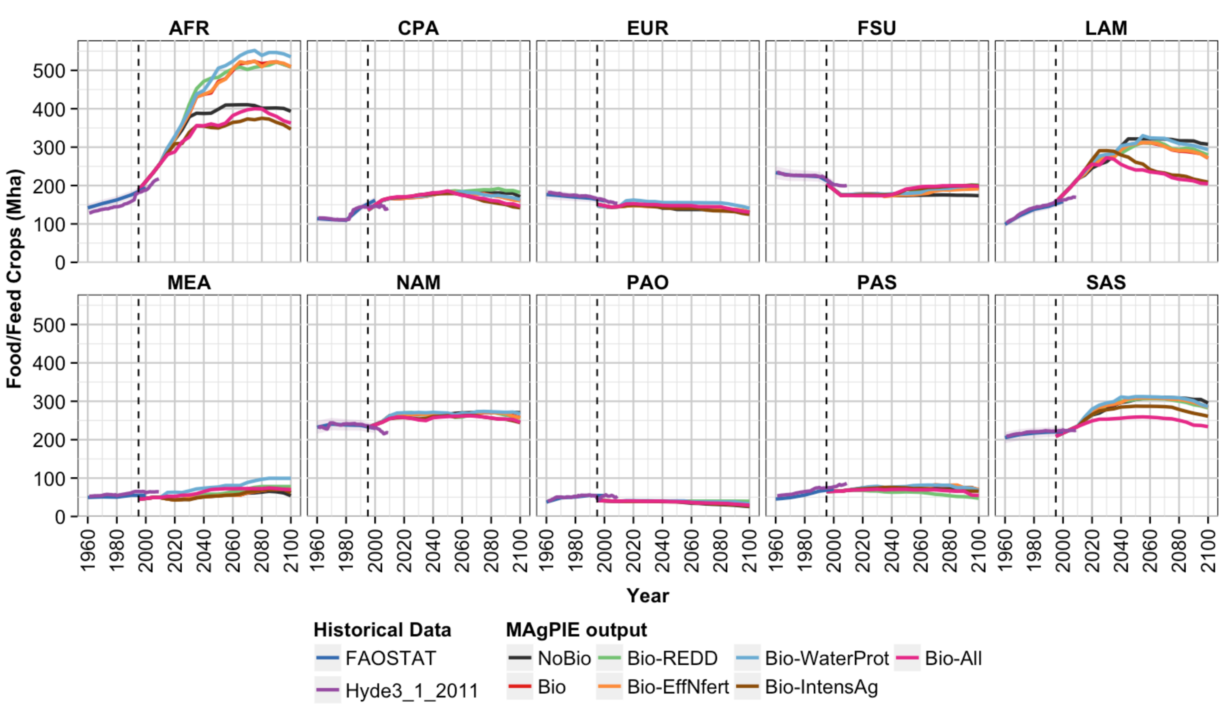
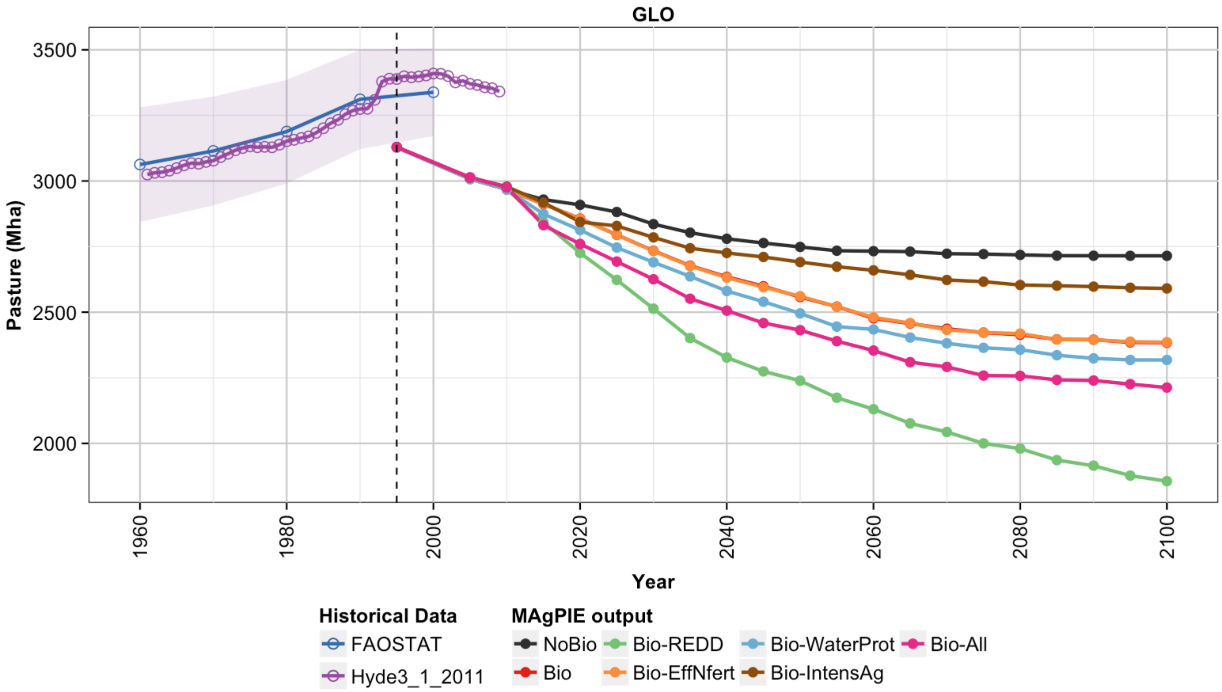


Figure S20| Time-series of scenario results for global (top) and regional (bottom) food/feed cropland (physical), compared to historical data from FAOSTAT[11] and HYDE 3.1[47]

4.2 Pasture

a)



b)

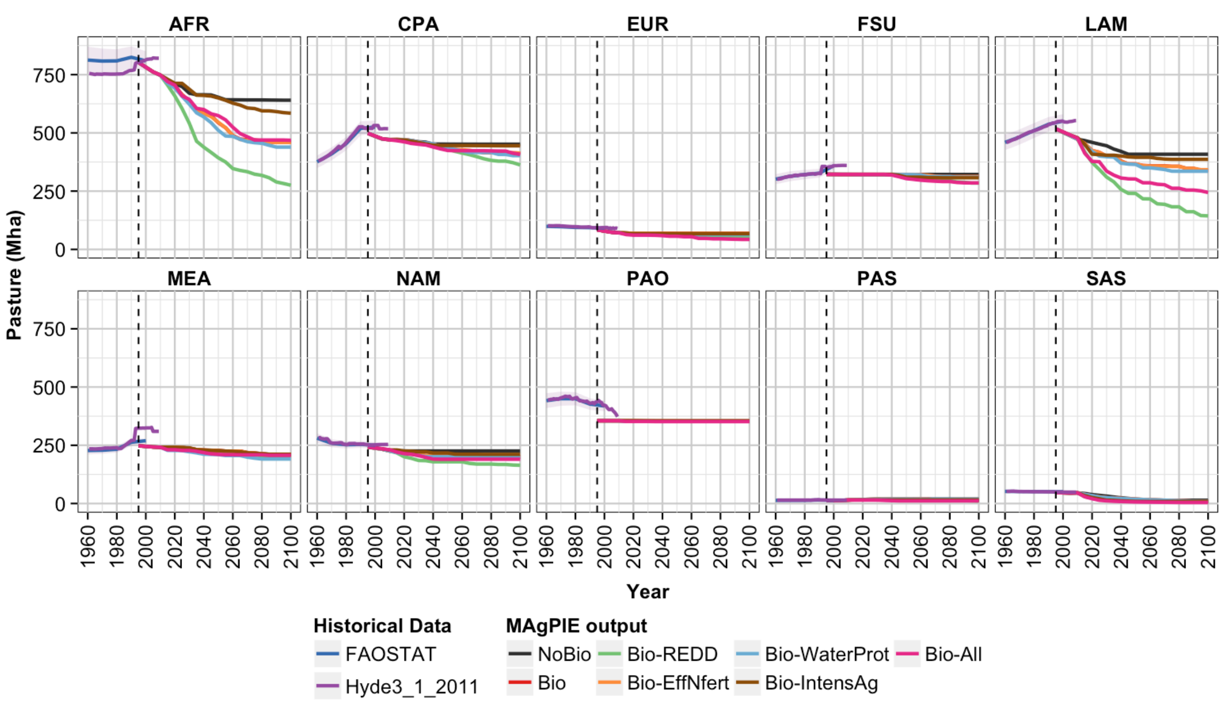


Figure S21| Time-series of scenario results for global (top) and regional (bottom) pasture area, compared to historical data from FAOSTAT[11] and HYDE 3.1[47]

4.3 Forest

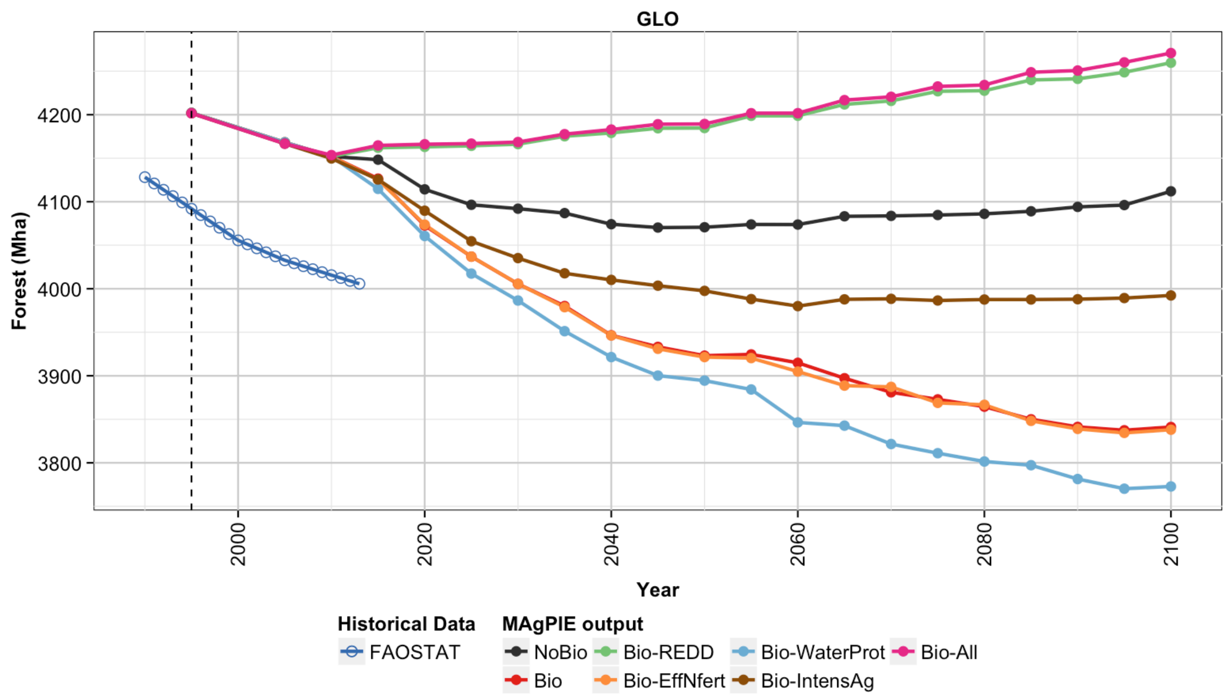


Figure S22| Time-series of scenario results for global forest area, compared to historical data from FAOSTAT[11]

4.4 Crop yield

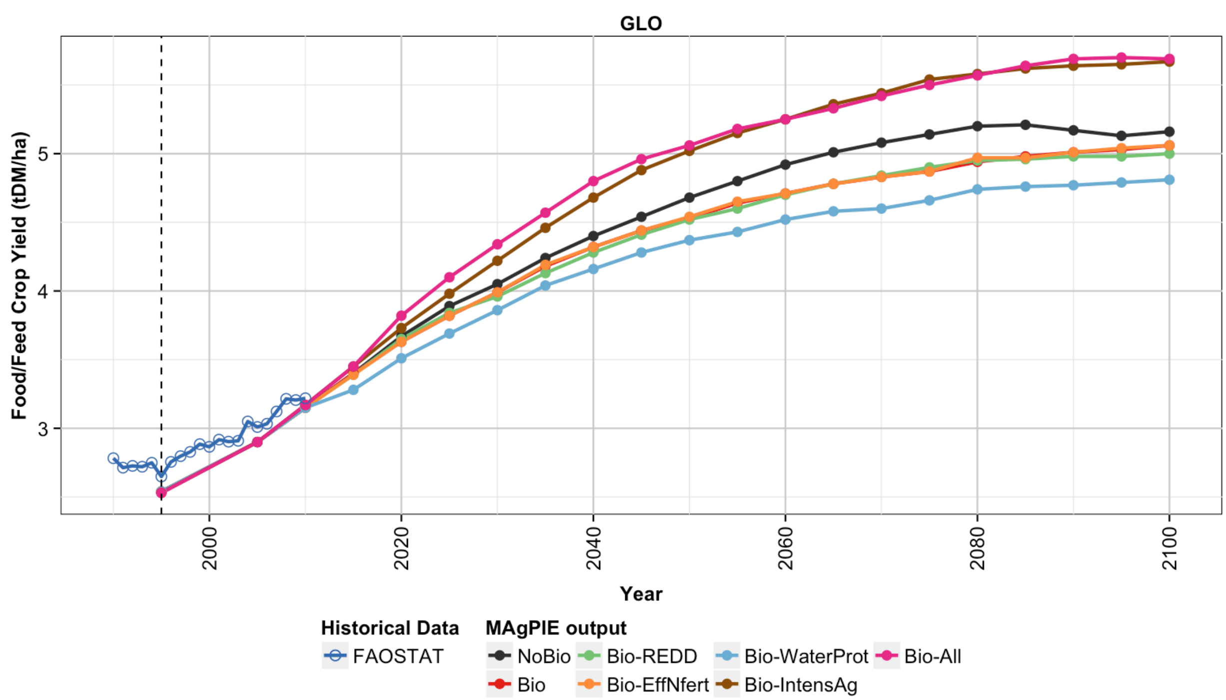


Figure S23| Time-series of scenario results for global food/feed crop yields (average over different crop types), compared to historical data from FAOSTAT[11]

4.5 CO2 emissions from land-use change

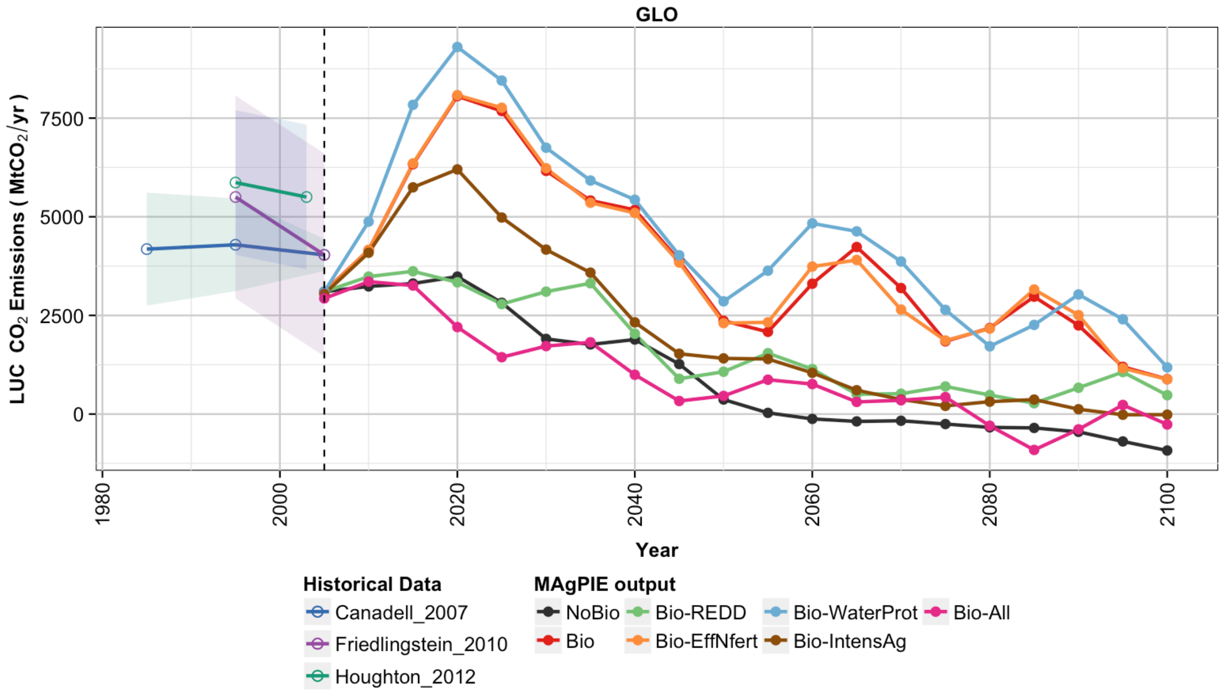


Figure S24| Time-series of scenario results for global land-use change emissions, compared to historical data from Canadell *et al*[48], Friedlingstein *et al*[49] and Houghton *et al*[50]

4.6 Nitrogen fertilizer use

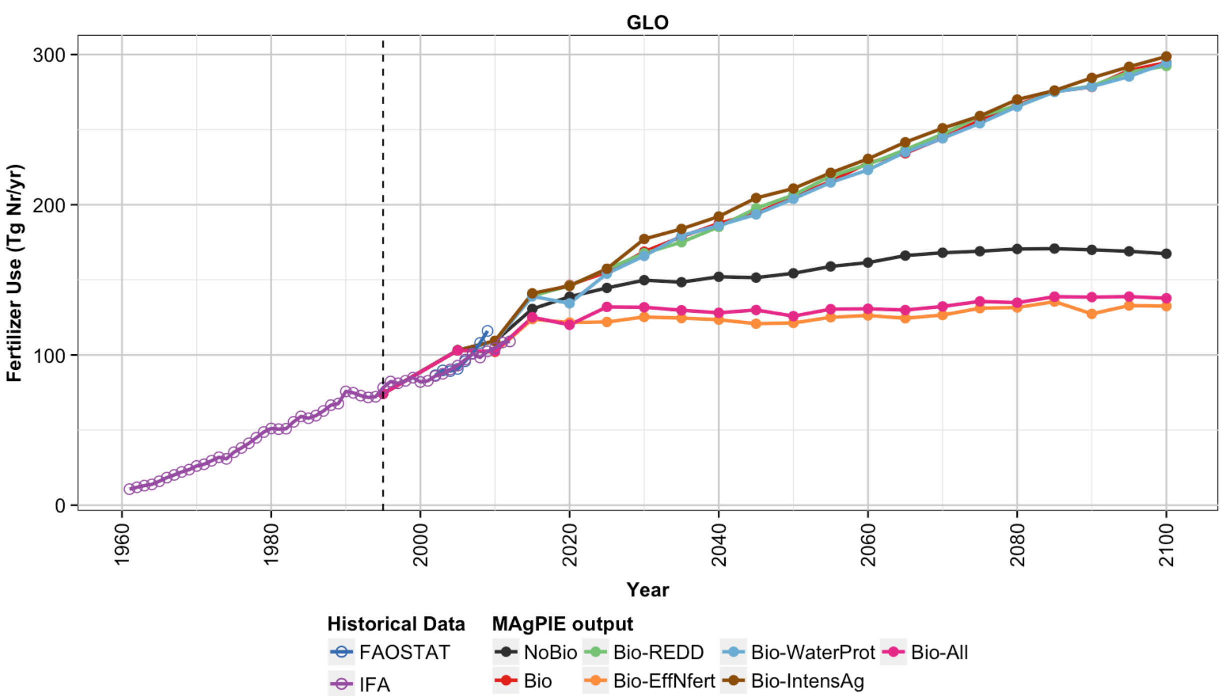


Figure 25| Time-series of scenario results for global inorganic nitrogen fertilizer application, compared to historical data from FAOSTAT[11] and IFA[51]

4.7 Water withdrawal

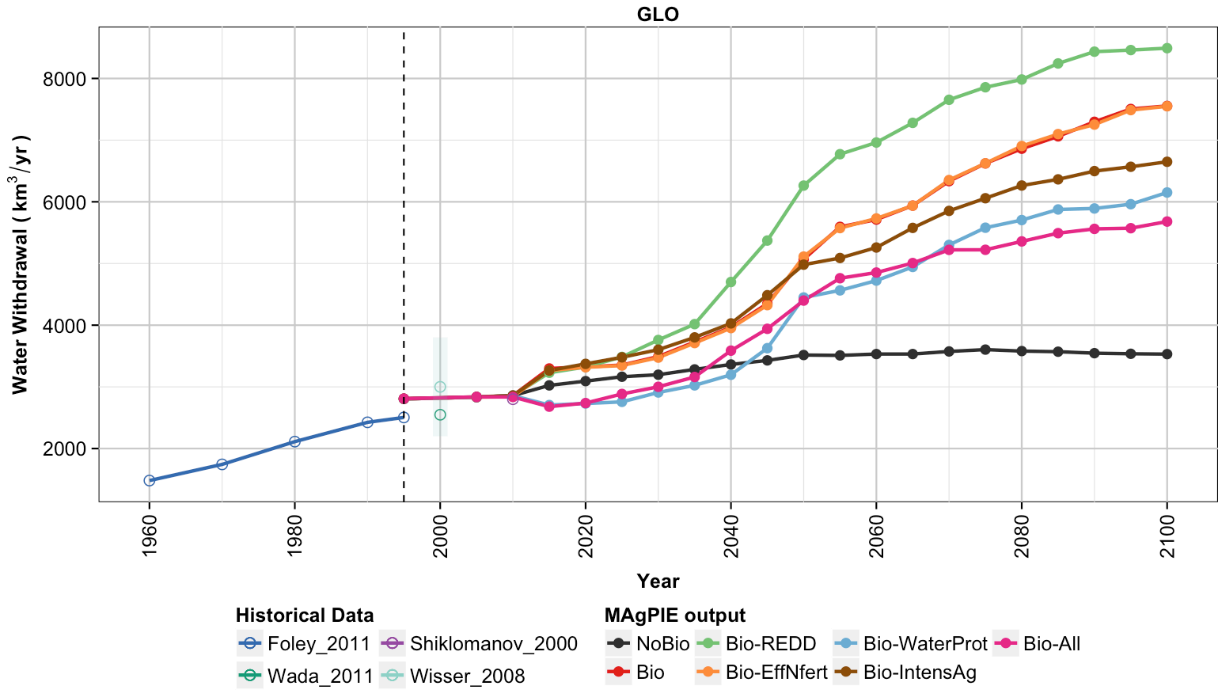


Figure 26| Time-series of scenario results for global agricultural water withdrawals, compared to historical data from Foley[52], Shiklomanov[53], Wada[54], Wisser[55].

4.8 Food price index

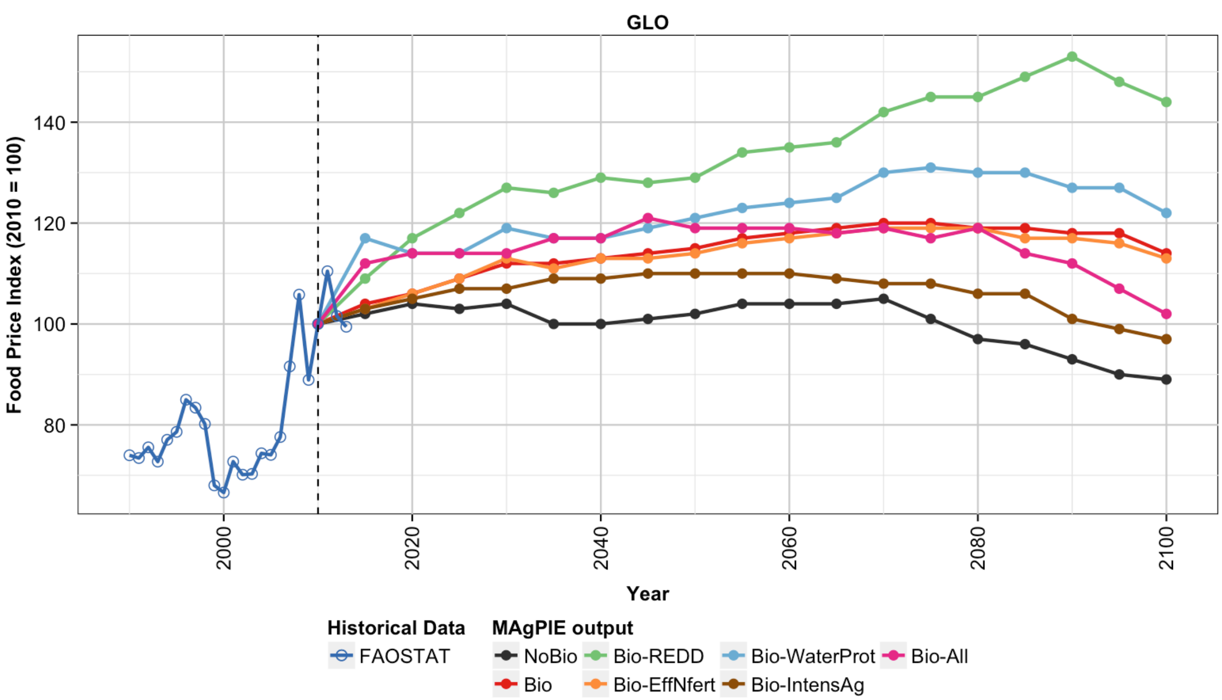


Figure 27| Time-series of scenario results for global food prices (Paasche price index), compared to historical data from FAOSTAT[11]

5 Regional scenario results

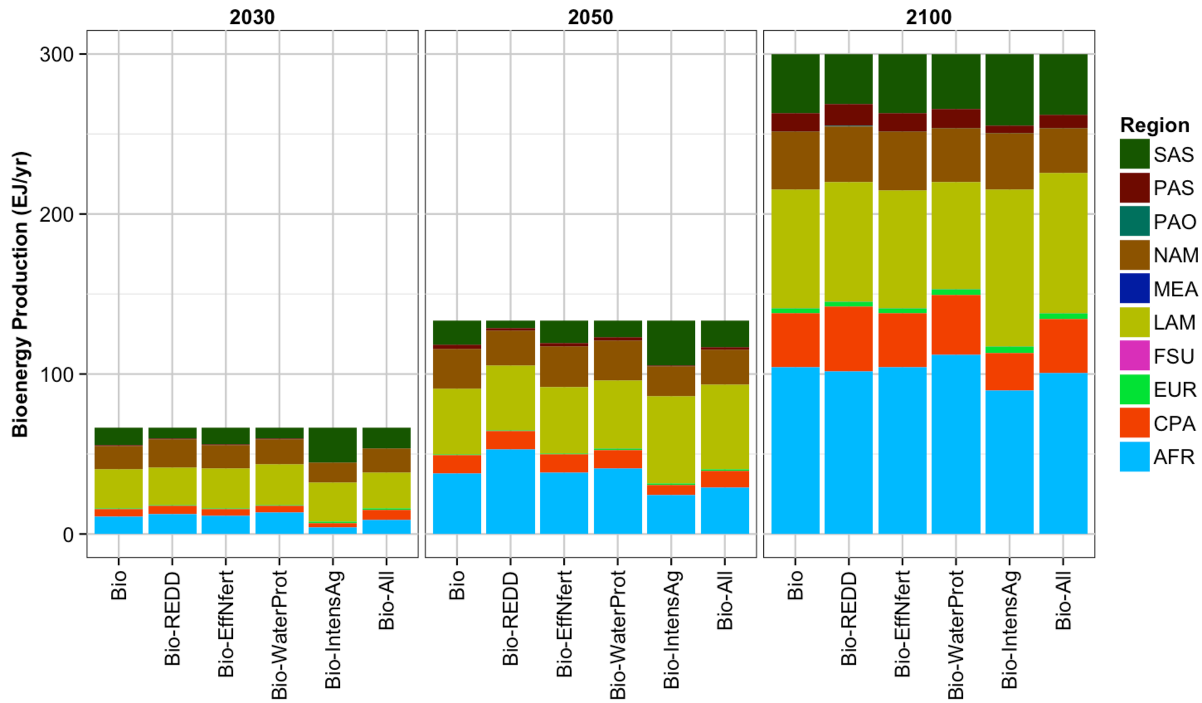


Figure S28| Regional bioenergy production. Given the global bioenergy demand trajectory (Figure S14), the model endogenously derives regional bioenergy production patterns based on cost-effectiveness.

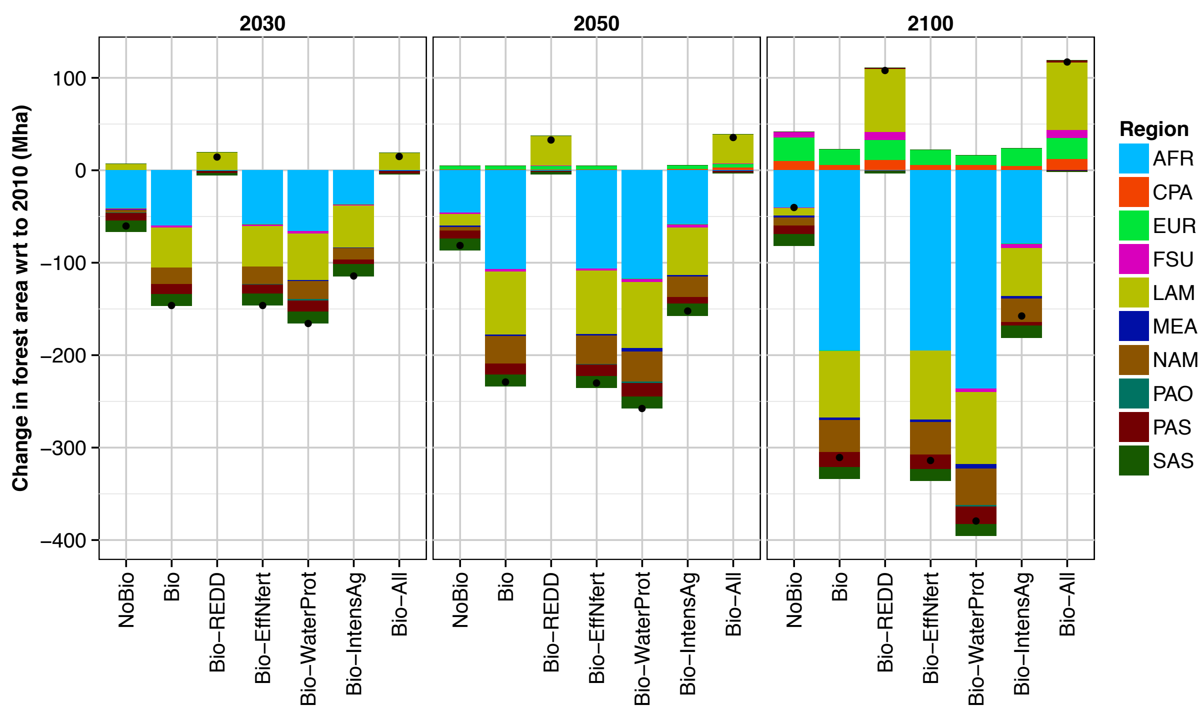


Figure S29| Regional change in forest area with respect to 2010

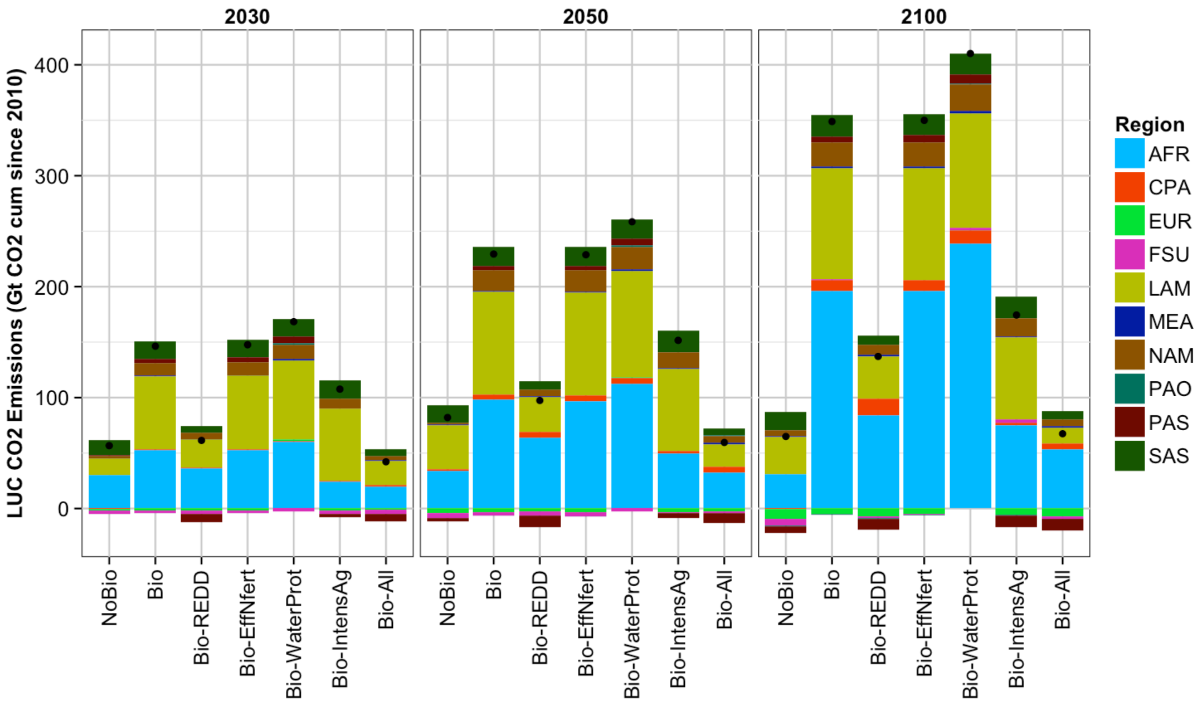


Figure S30| Regional cumulative LUC CO_2 emissions (2010 = 0)

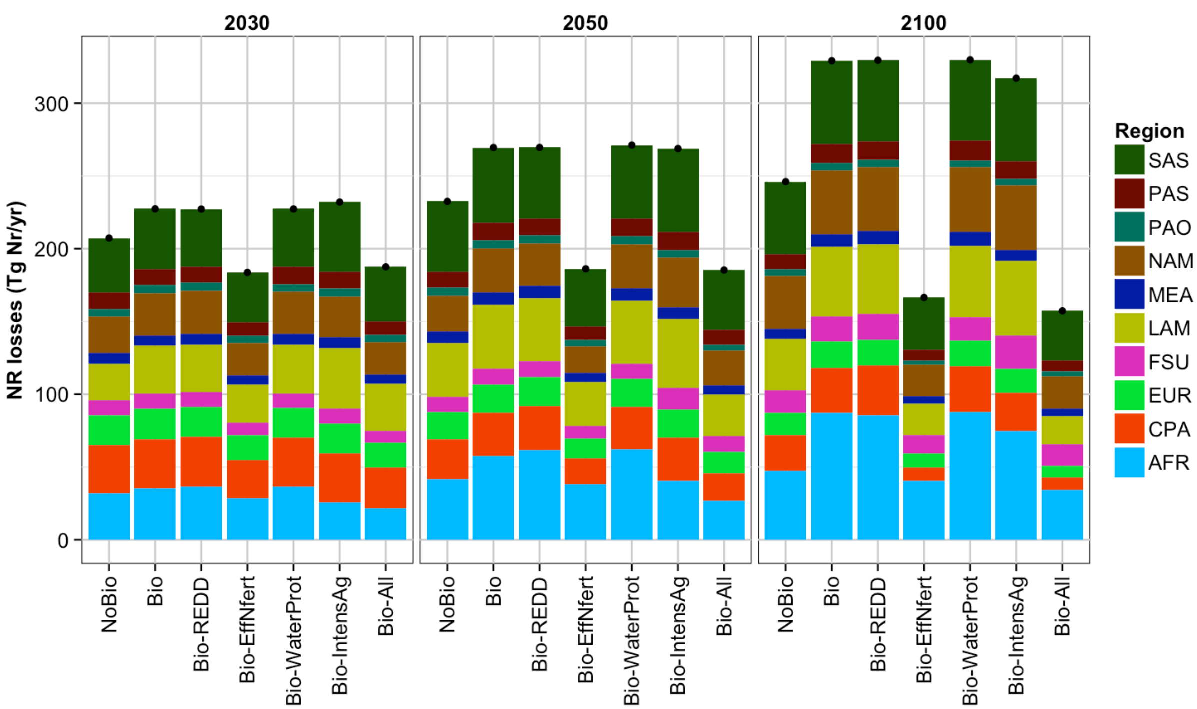


Figure S31| Regional nitrogen losses

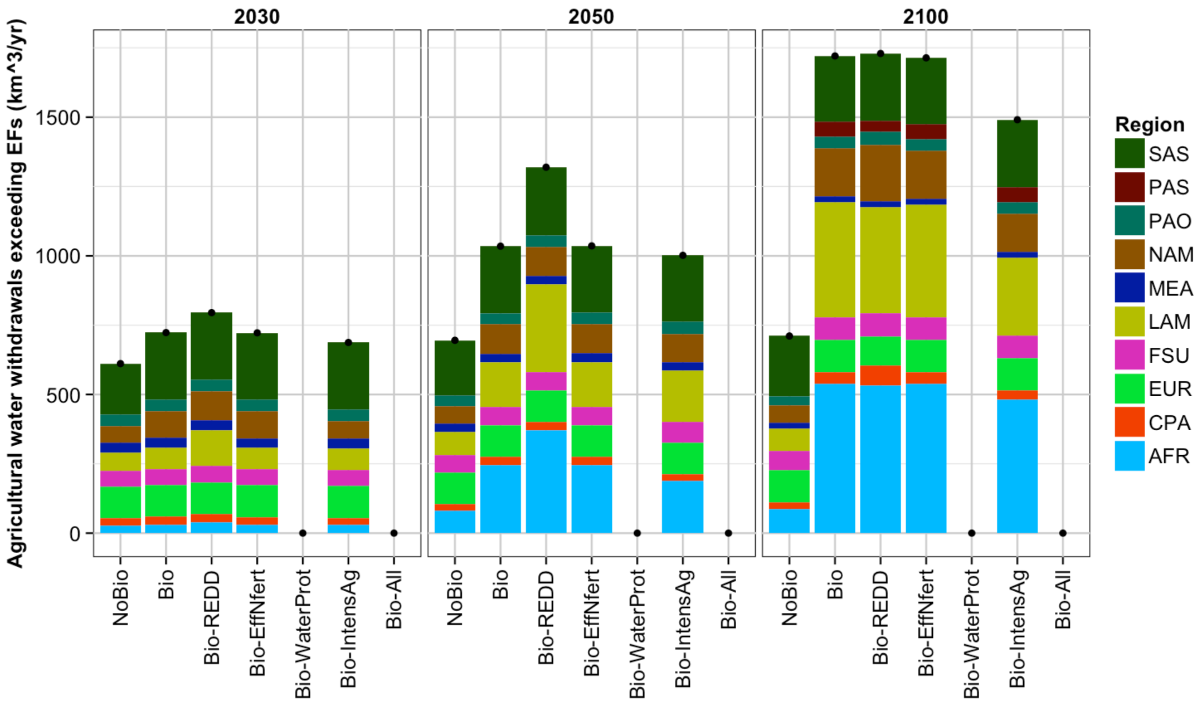


Figure S32| Regional water withdrawals for irrigation above environmental flow requirements

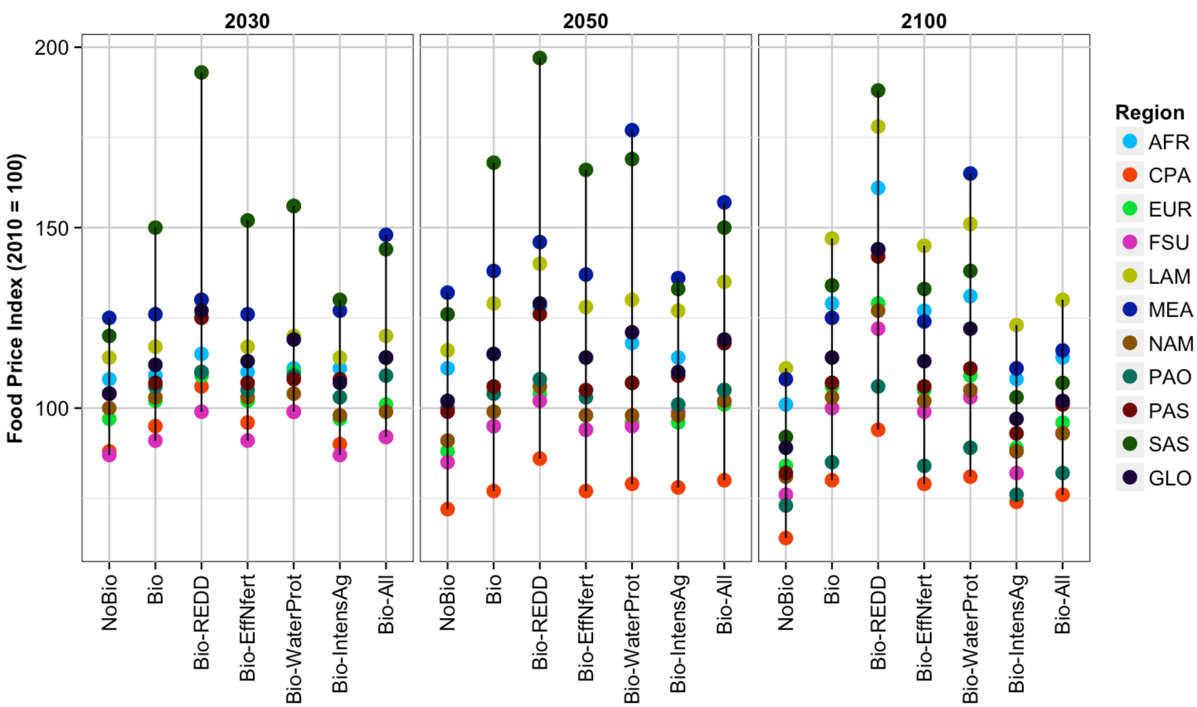
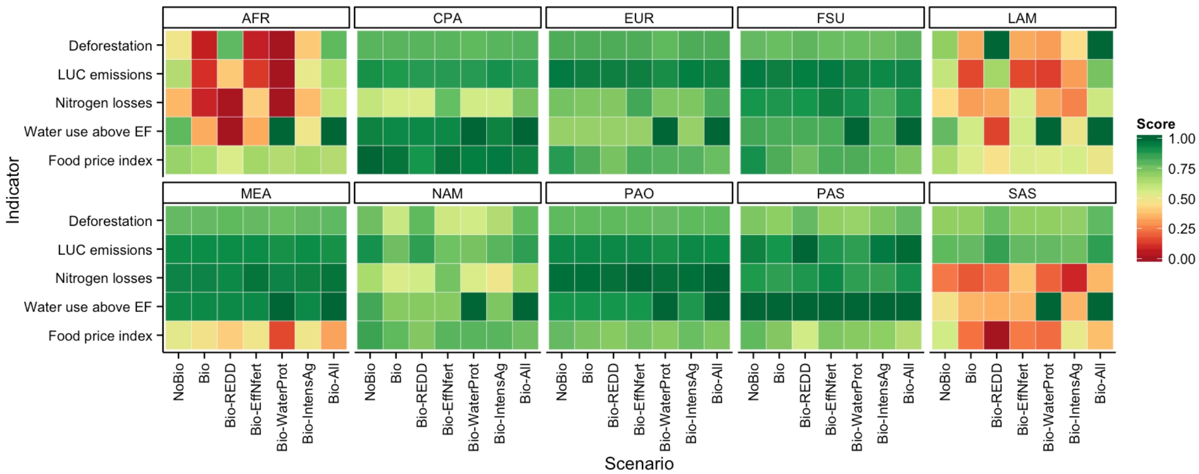


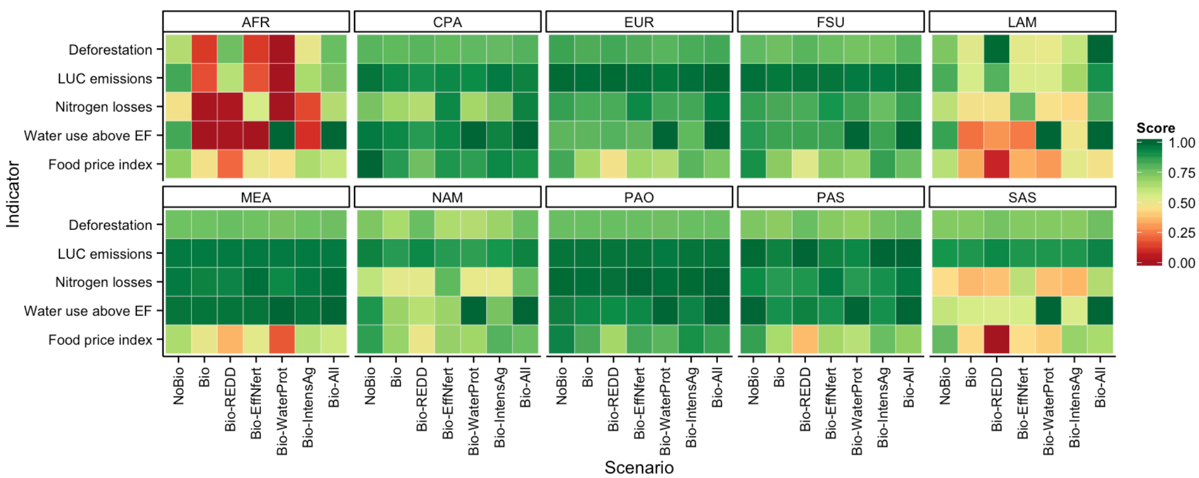
Figure S33| Regional and global food price index (2010 = 100) a)

2030



b)

2050



c)

2100

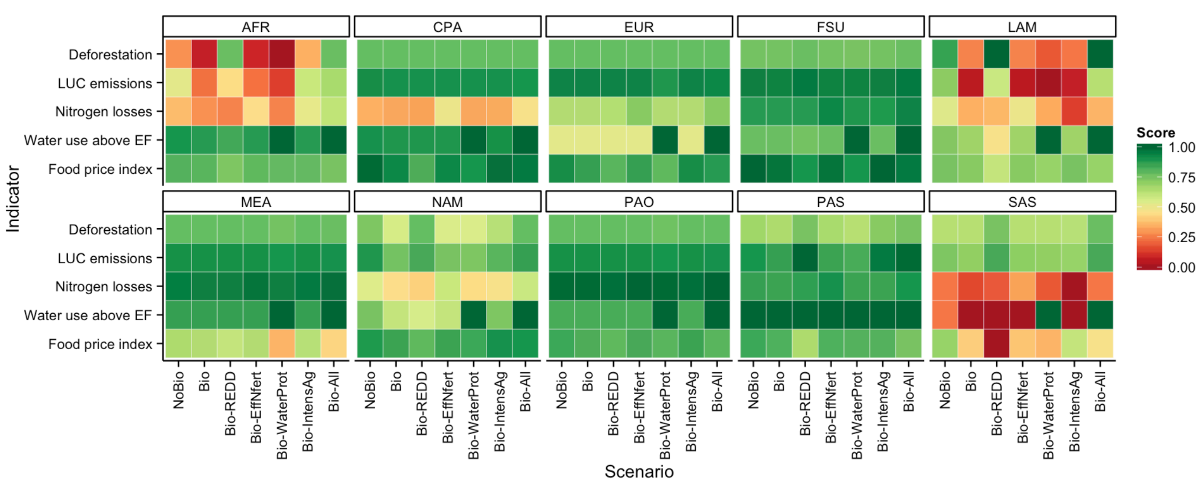


Figure 34| Summary of regional scenario results in 2030, 2050 and 2100. To facilitate straightforward comparison of scenario outcomes across all indicators, we calculate for each indicator normalized scores ranging between 0 and 1. First we determine the worst (0) and the best outcome (1) for each indicator across regions and scenarios and then align all outcomes in-between accordingly.

6 Scenario results without bioenergy

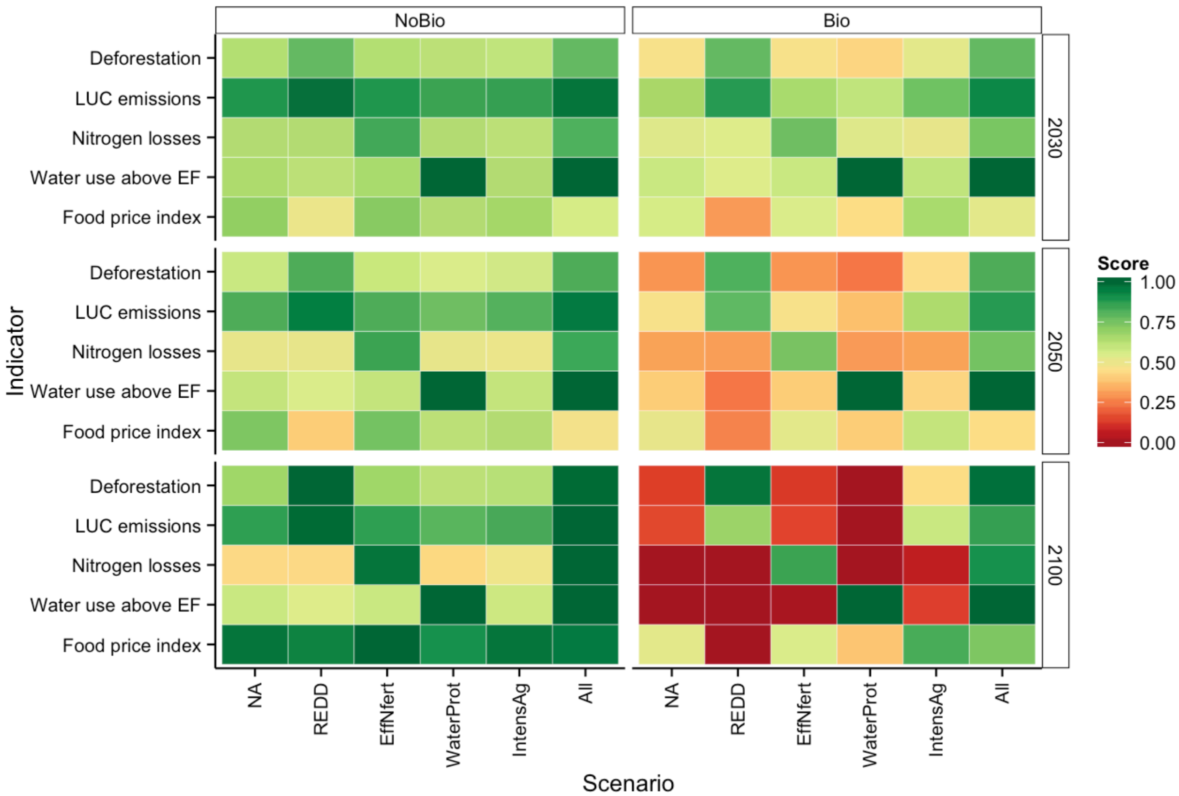


Figure S35| Scenario results with and without 2nd generation bioenergy production (Bio vs. NoBio). To facilitate straightforward comparison of scenario outcomes across all indicators, we calculate for each indicator normalized scores ranging between 0 and 1. First we determine the worst (0) and the best outcome (1) for each indicator across time and scenarios and then align all outcomes in-between accordingly.

7 Sensitivity analysis: higher irrigation efficiency

By default, we assume a global static value for irrigation efficiency of 66% in our scenarios until 2100. This value is the global weighted average of water losses from source to field (conveyance efficiency times management factor) from Ref[56]. Irrigated area from Ref[20] has been used as aggregation weight. While present day irrigation practices, which are largely based on surface irrigation, should be reflected well by our assumption, the adoption of more advanced irrigation technologies such as sprinkler and drip irrigation could substantially increase irrigation efficiencies in the coming decades. Currently, irrigation efficiencies are estimated 42-52% for surface irrigation, 69-78% for sprinkler irrigation, and 88-90% for drip irrigation[57]. To investigate how improvements of irrigation efficiency in the course of the 21st century affect our modelling results, we run an additional scenario (*EffIrrig*) with a linear increase of global irrigation efficiency from 66% to 89% throughout the 21st century.

Our sensitivity analysis shows that higher irrigation efficiency (*Bio-EffIrrig*) results in a slightly better overall indicator score outcome than environmental flow protection (*Bio-WaterProt*), mainly due to reduced deforestation and CO_2 emissions from land-use change, while unsustainable water withdrawals remain at relatively high levels. The combination of environmental flow protection and higher irrigation efficiency (*Bio-WaterProt-EffIrrig*) performs better than the two single measures because higher deforestation and CO_2 emissions caused by environmental flow protection are partly buffered by improvements in irrigation efficiency.

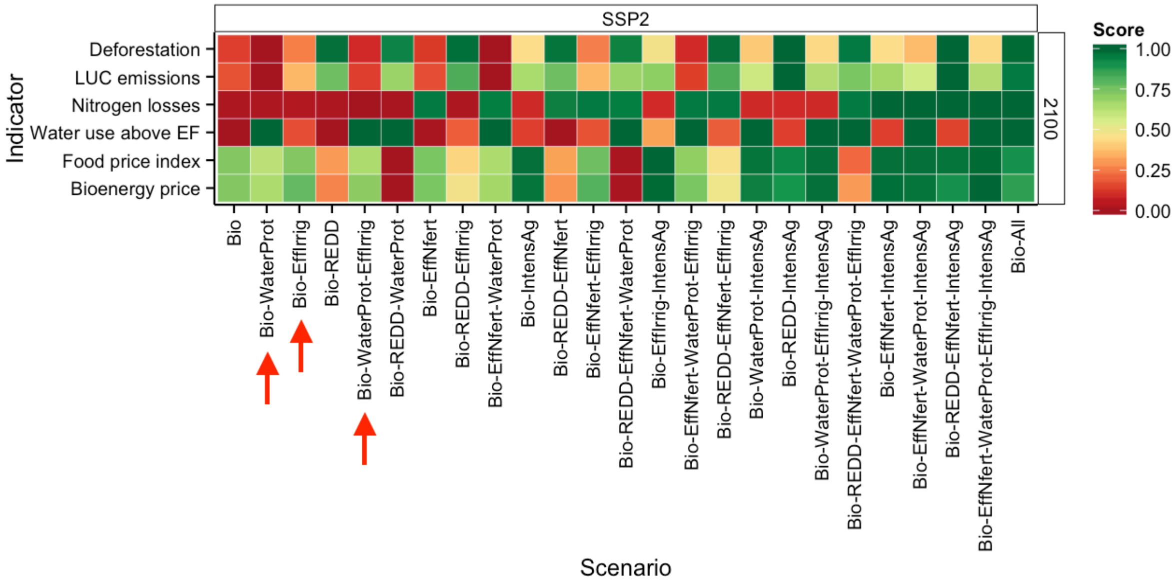


Figure S36| Results of sensitivity analysis for a scenario with increasing irrigation efficiency over time (*EffIrrig*). For comparability to other scenarios and scenario combinations, the figure layout is identical to Figure 4 in the main paper. Results are shown for year 2100 at the global scale. To facilitate straightforward comparison of scenario outcomes across all indicators, we calculate for each indicator normalized scores ranging between 0 and 1. First we determine the worst (0) and the best outcome (1) for each indicator across all scenarios and then align all outcomes in-between accordingly. Finally, we sort the scenarios according to the sum of the 6 indicator scores (best scenario is on the right-hand side).

8 References

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Annex 5

Bertram C, Luderer G, Popp A, Minx JC, Lamb WF, Stevanovic M, Humpenöder F, Giannousakis A, Kriegler E (2018) Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. Environ Res Lett 13:064038, doi:10.1088/1748-9326/aac3ec.

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Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios

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Abstract

Meeting the 1.5 °C goal will require a rapid scale-up of zero-carbon energy supply, fuel switching to electricity, efficiency and demand-reduction in all sectors, and the replenishment of natural carbon sinks. These transformations will have immediate impacts on various of the sustainable development goals. As goals such as affordable and clean energy and zero hunger are more immediate to great parts of global population, these impacts are central for societal acceptability of climate policies. Yet, little is known about how the achievement of other social and environmental sustainability objectives can be directly managed through emission reduction policies. In addition, the integrated assessment literature has so far emphasized a single, global (cost-minimizing) carbon price as the optimal mechanism to achieve emissions reductions. In this paper we introduce a broader suite of policies—including direct sector-level regulation, early mitigation action, and lifestyle changes—into the integrated energy-economy-land-use modeling system REMIND-MAgPIE. We examine their impact on non-climate sustainability issues when mean warming is to be kept well below 2 °C or 1.5 °C. We find that a combination of these policies can alleviate air pollution, water extraction, uranium extraction, food and energy price hikes, and dependence on negative emissions technologies, thus resulting in substantially reduced sustainability risks associated with mitigating climate change. Importantly, we find that these targeted policies can more than compensate for most sustainability risks of increasing climate ambition from 2 °C to 1.5 °C.

Background

Climate change and sustainable development have a long history in international diplomacy, and recent developments have attempted to merge the two agendas into a common discourse. Climate change has been enshrined in the sustainable development goals, as goal 13, whereas the Paris Agreement in turn has been strongly framed in the context of sustainable development (United Nations General Assembly 2015, UNFCCC 2015).

At the heart of this common discourse is a growing appreciation that both agendas directly depend on the success of the other (Stechow *et al* 2016). Arguably, sustainable development cannot be achieved unless the most severe, pervasive and potentially irreversible climate impacts of business-as-usual development to people and natural systems can be avoided—requiring limiting warming to well below 2 °C or possibly even 1.5 °C (Edenhofer *et al* 2014, IPCC 2014a). However, the means by which such emissions reductions would be achieved are highly consequential for future human development. For instance, a large-scale dependence on bioenergy and negative emissions deployments could threaten long-term food security and biodiversity objectives (Creutzig *et al* 2015, Fuss *et al* 2018, Minx *et al* 2018).

Conversely, it is becoming increasingly apparent that sustainable development is a key enabler for climate change mitigation. For instance, energy access

(SDG 7) and adequate food supply (SDG 2) are fundamental for livelihoods and poverty reduction (SDG 1), but they must be provisioned via low-carbon and sustainable infrastructures to avoid locking-in future emissions (Lamb and Rao 2015). Emissions reductions also require strong institutions (SDG 16), international partnerships (SDG 17), innovation (SDG 9), as well as healthy ecosystems (SDGs 13 and 14).

Many studies have explored the linkages between climate change mitigation and individual sustainability objectives. In the integrated assessment model (IAM) literature, streams of work have focused on climate policy in the context of household energy access (Riahi *et al* 2012, Pachauri *et al* 2013, Cameron *et al* 2016). Another series of studies have explored the economic implications of climate change mitigation, including policy costs in the short and long term, technological progress, carbon and energy price development, energy security aspects, and innovation and upscaling (Wilson *et al* 2013, Jewell *et al* 2014, Bertram *et al* 2015, Rogelj *et al* 2015). The wider impacts of climate change policies for other environmental problems such as local air pollution (West *et al* 2013, Strefler *et al* 2014), water scarcity (Bonsch *et al* 2016), deforestation, land-use change, and biodiversity have also been studied quite intensively (van Vuuren *et al* 2015), while social aspects have only been scarcely addressed (Stevanović *et al* 2017). Literature from a development angle has explored climate policy pathways that protect and enhance low-income livelihoods (Hallegatte *et al* 2016), potentially through targeted policies on high emitters and global reductions in inequality (Piketty and Chancel 2015, Rao and Min 2018), or by recycling carbon tax revenues into public goods (Jakob *et al* 2016).

Yet there have been few attempts so far to study synergies and trade-offs of mitigation policies across multiple sustainability objectives quantitatively (McCollum *et al* 2018). These studies typically include either a systematic assessment of existing research on individual SDG dimensions, within a matrix of potential policy measures (Weitz *et al* 2017), or integrated analysis examining the trade-offs between climate change mitigation, food security, biodiversity (van Vuuren *et al* 2015), food consumption and the land system (Obersteiner *et al* 2016). Research efforts from the sustainable development disciplines are also driving a 'energy-water-food nexus' framing, which has attracted both integrated modeling studies (Kyle *et al* 2013, Bonsch *et al* 2016) and bottom-up case studies (Biggs *et al* 2015, Keairns *et al* 2016). Still, a comprehensive assessment of sustainability implications associated with the 1.5 °C limit is so far unavailable. Such evidence is critical because stringent mitigation policy involves very aggressive efforts, including those that remove carbon dioxide from the atmosphere at a very large-scale (Luderer *et al* 2013, Rogelj *et al* 2015, Rogelj *et al* 2017). Furthermore, while increasing attention is given to the wider sustainability implications of mitigation policies, there is little analysis so far regarding how these can be directly managed through the choice of alternative mitigation policies.

Against this background, the goals of our study are to: (a) quantify the potential benefits and adverse side-effects of climate change mitigation on sustainability indicators, both for 2 °C and 1.5 °C; (b) evaluate the effectiveness of different policies in fostering sustainable development; and (c) understand the trade-offs implied by single instruments and their complementarity.

Methods

In this study, we provide an integrated analysis of sustainability impacts of 1.5 °C and 2 °C scenarios, across a comparatively large number of sustainability dimensions, and analyze how policy packages addressing climate and non-climate objectives can help to manage wider sustainability impacts.

We use the integrated energy-economy-climate model REMIND (Leimbach *et al* 2010, Luderer *et al* 2015) coupled to the land-use model MAgPIE (Lotze-Campen *et al* 2008, Popp *et al* 2014). Further details on the two models and their coupling can be found in supplementary section 1 available at stacks.iop.org/ERL/13/064038/mmedia. Within this modeling framework, we construct various transformation pathways that lead to two different long-term climate targets and are differentiated by five different policy paradigms. In terms of the socio-economic development of population, GDP, trade, and development of technology cost and availability, middle-of-the road assumptions as in the SSP2 scenario (Fricko *et al* 2017) are underlying all scenarios. Scenarios are differentiated along the two dimensions of climate stabilization target and policy paradigm.

Stabilization target: For the long-term climate target, we investigate both a 'well-below 2 °C' scenario and a '1.5 °C by 2100' scenario (table 1). As in Luderer *et al* (2018) the climate targets are defined via a bound on cumulative total CO_2 emissions (including emissions from fossil fuel combustion, industrial processes and land-use and land-use change). The bound is adhered by iteratively adjusting the emissions price on CO_2, N_2O and CH_4, using 100 year global warming potentials, with reduced prices for emissions from the land-use system (cf. table 2). Emission pricing starts in 2020 and prices increase exponentially until 2060 with 5% p.a. in the default policy setting and linearly thereafter. For the well-below 2 °C target, cumulative 2011–2100 net emissions are limited to 1000 Gt CO_2, whereas the 1.5 °C scenario has a budget of 400 $GtCO_2$. These budget values represent a likelihood of 66% of staying below 2 °C throughout the 21st century in the 'well below 2 °C' scenarios, as well as 66% of staying below 1.5 °C after 2100 in the 1.5 °C scenario (Clarke *et al* 2014, Luderer *et al* 2018).

Table 1. Overview of scenarios. For a complete list of policies included in each of the policy paradigm cases and further explanations, see table 2.

		Policy paradigm				
		Default	Regulation	Early action	Lifestyle	Sustainable
		Carbon price increasing at 5% p.a.	Water and forest protection; Nuclear phase-out; Fossil subsidy phase-out	Higher initial carbon price increase at 3% p.a.	Healthier diets; Lower energy use	***Regulation, early action, lifestyle*** policy approaches combined
Stabilization target	**Reference** (no mitigation)	**REF_Def**				**REF_Sust**
	Well below 2 °C limit	**2 °C_Def**	2 °C_regul	2 °C_early	2 °C_lifesty	**2 °C_Sust**
	1.5 °C limit	**1.5 °C_Def**	1.5 °C_regul	1.5 °C_early	1.5 °C_lifesty	**1.5 °C_Sust**

Policy paradigm: As a reference case for the analysis of stabilization scenarios, we design a default climate-only policy scenario following cost-effective achievement of climate targets via a globally and sectorally harmonized carbon price increasing exponentially at 5% p.a. in real terms. In a second step we add combined policy packages deviating from the least-cost paradigm by imposing dedicated technology and management *regulations* in the land and energy sectors, increased *early action* mitigation and *lifestyle* changes towards less material, energy, and land intensive-lifestyles (table 2), on top of the carbon price. Criteria for the choice of policy elements are that they have an intuitive linkage to identified sustainability risks of mitigation, and that they can be represented in our modeling framework in a meaningful way. The list is therefore not necessarily exhaustive, and the purpose of grouping elements into the three distinct policy paradigms serves to illustrate crucial characteristics and interactions. Since these additional policies influence the portfolio of mitigation options, they typically also change the carbon price required to achieve the same climate target (supplementary figure S7). The additional policy elements are either implemented by adding bounds to the solution space (for example requiring a certain share of new vehicle sales to be electric), by assuming a different value for a certain input parameter (food and baseline energy demand, for example, are input parameters to the model), or by adjusting the temporal profile of carbon price trajectories (early action scenario).

Table 2 lists the elements of the policy strategies that are analyzed in this study, and how they are combined for the three individual policy paradigm cases 'Regulation', 'Early action', and 'Lifestyle'. Further description on the implementation of policies can be found in supplementary section 3.

Indicator selection: We develop customized indicators that capture global stressors for individual SDGs in our global modeling framework. In case of an increase of the stressor level due to mitigation, we speak of a sustainability risk of mitigation, using the broad IPCC usage of the term 'risk' (IPCC 2014b). Table 3 lists the 12 indicators used in this study and indicates relevant links to SDGs. We took the freedom of mapping indicators to SDGs based on the underlying transformation requirements of SDGs, abstracting from the official sub-targets and related indicators of them. While no indicator alone is able to fully capture any of the SDGs, and the time-frame of the analysis is mostly for 2030–2050, 10 of the 17 SDGs receive at least some coverage in this analysis.

The indicator selection is constrained by the scope of the REMIND and MAgPIE models. For instance, food prices do not fully address nutritional and calorific needs; aggregate water withdrawal does not reflect region specific limits; while cost indicators may not capture distributional burdens. The divergence between a pragmatic and ideal indicator selection is, however, a feature of all sustainability studies (Jones *et al* 2016).

While acknowledging the regional heterogeneity of sustainability impacts and the political importance of evaluating SDGs on the country level, we here deliberately focus on impact indicators aggregated to the global level. This approach offers greatest conceptual clarity in quantifying crucial synergies and tradeoffs between climate change mitigation and other sustainability objectives. Importantly, we do not attempt to monetarize all sustainability risks in order to minimize an aggregate overall risk indicator. We also refrain from defining thresholds for intolerable risk levels in the various sustainability dimensions, given that this involves value judgments and that for many indicators it is impossible to derive meaningful global-level thresholds. Regarding the temporal scope of the analyzed indicators, we have chosen the time frame until which most of the impacts of policy choices have materialized. Therefore, the analysis goes beyond the target year of SDGs (2030), as many of these are only milestones on a longer transformation that we capture in our analysis. Further explanations on the choice, limitation, and definition of the used indicators can be found in supplementary section 4.

Table 2. Overview of settings in the different policy paradigms scenarios.

Policy element	Setting in default scenarios	Policy setting	Policy setting active in scenario.... Regulation	Early action	Lifestyle	Sustainability
Trade in agricultural products (Schmitz *et al* 2012)	Agricultural trade barriers (i.e. the amount of the trade pool with trade according to historic patterns) decline by 0.5% per year	Agricultural trade barriers decline by 1% per year ('Policy scenario' in Schmitz *et al* 2012)	X			X
1st generation biofuels (Lotze-Campen *et al* 2010)	Constant at 2020 levels	Phase-out	X			X
Water protection (Bonsch *et al* 2015)	No dedicated measure	Protection of water resources based on environmental flow requirements resulting in around 40% lower agricultural water withdrawals in 2050 globally	X			X
Forest protection (Popp *et al* 2017)	Linear increase of protected forest areas by factor 1.5 between 2010 and 2100	Linear increase of protected forest areas by factor 4 between 2010 and 2100	X			X
Nitrogen efficiency (Bodirsky *et al* 2014)	Soil nitrogen uptake efficiency converges to 60% globally by 2050; constant thereafter	Soil nitrogen uptake efficiency converges to 75% globally by 2050, and rises to 85% by 2100	X			X
Agri. waste management systems (Bodirsky *et al* 2014)	30% adoption rate for anaerobic digesters by 2050.	60% adoption rate for anaerobic digesters by 2050.	X			X
Feeding convergence (Popp *et al* 2017)	Faster increase of productivity in low income countries; continuing increase in high income countries.	20% more efficient	X			X
Nuclear power (Bauer *et al* 2012)	No constraint	No new plants after 2020	X			X
CCS injection	Flow constraint of 1% of total reservoir capacity per year	Flow constraint of 0.5% of total reservoir capacity per year	X			
Electric vehicles (IEA 2016)	No dedicated support	Dedicated support, mandating 8, 5 and 2% LDV market share in different regions in 2020, each rising by 2% points per year afterwards (capped at 80%, reached around 2060)	X			X
Carbon pricing	Exponential increase at 5% p.a. from 2020–2060, linear increase thereafter	Exponential increase at 3% p.a. from 2020–2060, linear increase thereafter		X		X
Pricing of land-use emissions	50% of price level in the energy system	25% of price level in the energy system		X		X
Early retirement of coal power plants	Max 6% linearly per year (full phase-out earliest in 2035)	Max 10% linearly per year (full phase-out earliest in 2030)		X		X
Fossil fuel subsidies (Schwanitz *et al* 2014, Bertram *et al* 2015)	Phase-out until 2050	Phase-out until 2030		X		X

Table 2. *Contined.*

Policy element	Setting in default scenarios	Policy setting	Policy setting active in scenario.... Regulation	Early action	Lifestyle	Sustainability
Final energy demand	SSP2 (~700 EJ in 2050, 900 EJ in 2100)	SSP1 per capita demand with SSP2 population assumptions: −25% at the end of the century (~600 EJ in 2050, 700 in 2100)			X	X
Agricultural demand (Bodirsky *et al* 2014, Stevanović *et al* 2017)	Continuation of current trends, with doubling of total food demand by the end of the century, caused by the increase in population and income.	−20% below reference overall at the end of the century, 50% for livestock products			X	X

Table 3. Analyzed indicators and relevant SDGs. Please note that the cost indicators do not take into account avoided damages due to lower warming, as the modeling framework does not yet include climate feedbacks and damages. For further explanations on the indicators, see the list in supplementary section 4.

Indicator	Relevant SDG
Food price index in 2030	SDG 2 (Zero hunger)
Water withdrawal for irrigation and power generation in 2030	SDG 6 (Clean water and sanitation)
Short-term costs (cumulative consumption losses from 2015–2050)	SDG 1 (No poverty)
Long-term costs (cumulative consumption losses from 2050–2100)	SDG 8 (Decent work and economic growth)
SO_2 emissions from power generation in 2030	SDG 3 (Good health and well-being)
Temperature increase in 2050 relative to 2015	SDG 13 (Climate Change)
Cumulative uranium extraction 2015–2100	SDG 12 (Responsible consumption and production)
Cumulative extraction of fossil fuels	SDG 12 (Responsible consumption and production)
Cumulative sequestered CO_2 2015–2100	SDG 12 (Responsible consumption and production)
Energy price index in 2030	SDG 7 (Affordable and clean energy)
Cropland for bioenergy crops (average 2050–2100)	SDG 15 (Life on Land)
Fertilizer use in 2030 (Nitrogen)	SDG 14 (Life below water)

Results

The 2 °C and 1.5 °C scenarios in this study broadly share general transformation characteristics with comparable scenarios of the literature (Rogelj *et al* 2013, 2015, Luderer *et al* 2013) (figure 1). 2 °C pathways are characterized by a peaking of CO_2 emissions by 2020, steep emission reductions through mid-century, and CO_2 neutrality or net-negative emissions in the second half of the 21st century. For 1.5 °C pathways, near-term emissions reductions are even faster, and CO_2 neutrality is achieved around mid-century. Decarbonization is achieved by a fast ramp-up of various low-carbon energy types, electrification of end-use (supplementary figures S1 and S4), as well as a strong transformation of land-use (supplementary figures S5 and S6).

The choice of policy approach alters the scale and timing of decarbonization, so that the scenarios with the complete set of additional policy packages ('_Sust') show an earlier and faster decarbonization process than in the existing literature. Therefore emissions during the second half of the century remain higher in comparison to the default mitigation policy scenarios, although there are more negative emissions from afforestation throughout the century, with a peak around mid-century (figures 1(*a*),(*c*)). The 1.5 °C_Sust scenario therefore reaches net-negative emissions already before 2050, but maximum total net negative emissions are at around 7 Gt CO_2 yr^{-1} compared to 13 Gt CO_2 yr^{-1} in the 1.5 °C_Def scenario. The share of low-carbon technologies (renewables, nuclear and fossils with carbon capture and storage (CCS), figure 1(*b*)) shows, compared to existing scenarios, relatively low values for the sustainable scenarios at the end of the century. The reason is that the faster decarbonization in the first half leaves more room for the later use of oil in sectors that are projected to remain dependent on non-electric fuels, which are mostly provided by biofuels in default policy scenarios. Electrification is higher throughout the century in scenarios with additional sustainability policies, and due to the dedicated policies on electric mobility shows a faster near-term increase than the scenarios from previous studies (supplementary figure S1).

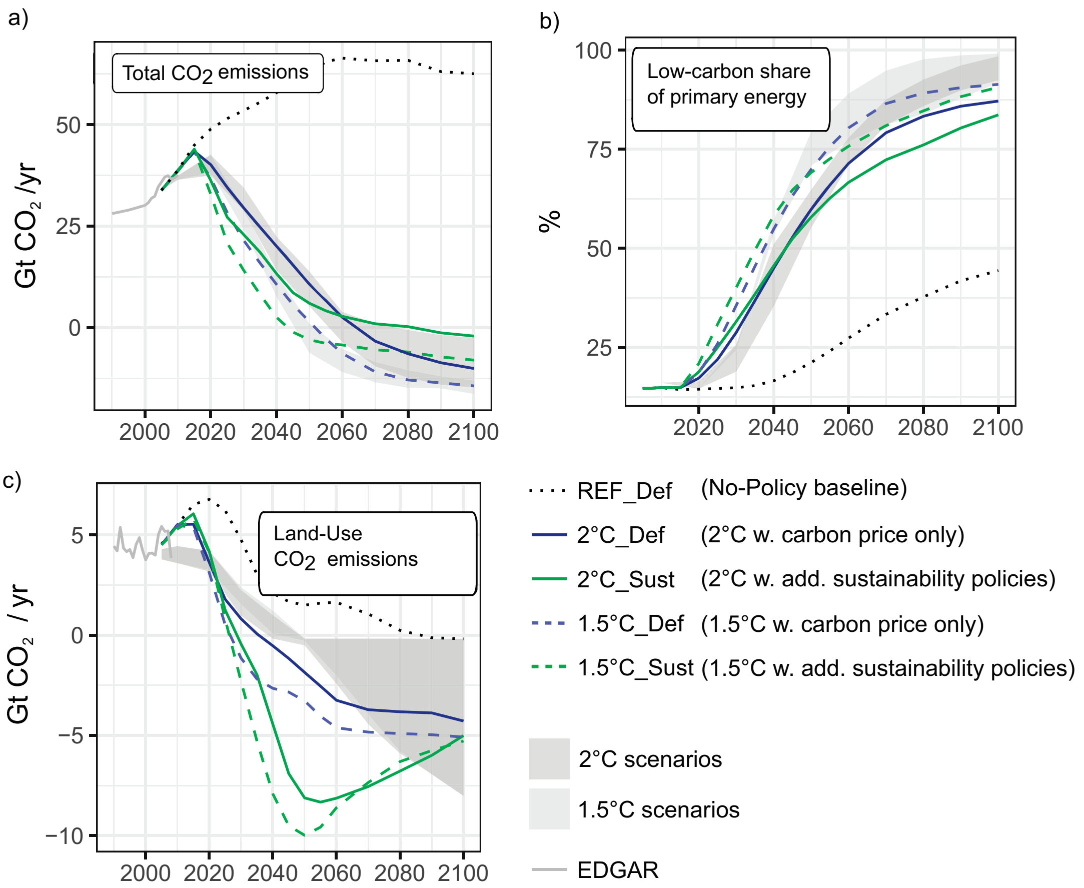

Figure 1. General transformation characteristics in the five main scenarios. (*a*) Total CO_2 emissions, (*b*) share of low-carbon technologies in total primary energy supply (using direct equivalent accounting method and considering renewables, nuclear and fossils with CCS as low-carbon) and (*c*) land-use CO_2 emissions. Historic emission data is from EDGAR (EDGAR 2011) and the grey funnels in the background show the scenarios from previous studies on 1.5 °C and 2 °C scenarios (Rogelj *et al* 2013, 2015, Luderer *et al* 2013), selecting those scenarios with a start of ambitious climate policies in 2015 or 2020. Supplementary figure S1 additionally shows CO_2 emissions from fossil fuel and industry, food price developments over time and the share of electricity in total final energy.

Benefits and risks of 2 °C mitigations pathways

Our default mitigation-only policy scenarios toward 2 °C (2 °C_Def) highlights benefits and risks associated with mitigation in non-climate dimensions (called 'sustainability benefits/risks of mitigation' from now on) (figure 2(*b*)) (Jakob and Steckel 2016, Stechow *et al* 2016). Reduced air pollution from fossil fuel use, and the reduction of temperature increase until 2050 by more than 0.5 °C compared to the no-policy reference scenario (REF_Def) feature as important benefits of mitigation. Furthermore, near-term water withdrawal for irrigation and power generation is slightly reduced due to a lower deployment of thermal power generation technologies.

Uranium and fertilizer use increase slightly in the 2 °C scenario compared to the baseline, as higher carbon prices lead to a further increase of nuclear power and bioenergy. The demand for biomass, together with carbon pricing for land-conversion emissions, limit land available for food production, such that the 2 °C scenario with default pricing-only climate policies leads to a pronounced increase of 35% in food prices in 15 years, roughly double the projected increase in the no-policy reference scenario.

Clear sustainability risks of mitigation emerge for energy price increases, short and long-term mitigation costs, as well as land requirements for bioenergy and geological CO_2 sequestration. The 2 °C scenario with default policies results in an increase of energy prices of around 45%, more than double the increase without climate policy. A crucial technology option in our scenarios is the combination of bio-energy with carbon capture and geological sequestration (BECCS). This combination leads to removal of carbon dioxide from the atmosphere and thus can offset some of the residual emissions that are difficult to avoid (such as fossil fuel use for freight transport, aviation and shipping, as well as certain industrial processes and non-CO_2 greenhouse gas emissions from agriculture (Gernaat *et al* 2015)). Our analysis distinguishes two important sustainability risks of BECCS, illustrated by the requirement for land and geological reservoirs. In the default pricing-only 2 °C scenario, close to 300 million ha of crop-land are dedicated for growing energy crops on average between 2050 and 2100, and a cumulative total of more than 700 Gt CO_2 is sequestered in geological formations in this century, 65% of which originate from BECCS. Finally, economic risks

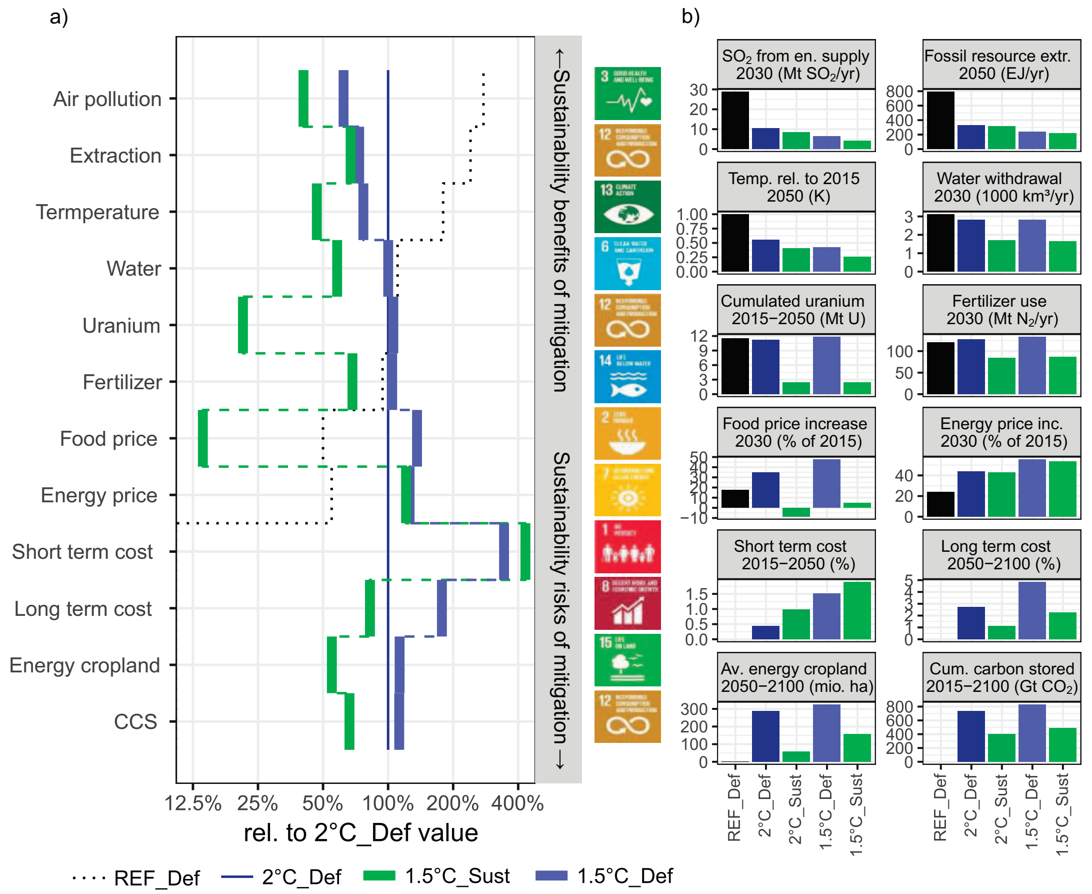

Figure 2. Comparative analysis of both policy approaches and long-term targets. Sustainability indicators for 2 °C and 1.5 °C scenarios with mitigation-only policy (Def) and combined sustainability policy package (Sust). Panel (*a*) shows values relative to the 2 °C_Def scenario in logarithmic scale, panel (*b*) shows the absolute values for all five main scenarios and additionally indicates the time/time-span shown. All values are global totals or averages. Indicators are arranged such that the most pronounced sustainability benefits of mitigation sit on top, and the most severe sustainability risks at the bottom. This ranking is based on the relative values, and does not imply a normative weighting of the different dimensions which can only emerge from broad public deliberations. Please note that the 2 °C_Sust scenario is only shown in panel (*b*), in order to provide a clear overview in panel (*a*). A version of panel a including 2 °C_Sust is provided as supplementary figure S2.

associated with mitigation are limited in the default 2 °C scenario with less than 0.5% of consumption losses on average during the first 35 years and about 3% during the second half of the 21st century.

1.5 °C shows higher benefits but also increased risks than 2 °C

Both sustainability benefits and risks of mitigation increase further when the long-term mitigation target is strengthened from 2 °C (2 °C_Def) to 1.5 °C scenarios (1.5 °C_Def) with default policies. In the mid-century warming indicator, there is only limited improvement possible (0.13 °C), as the inertia of both capital stocks and the climate system has already locked-in a certain amount of warming until mid-century. Yet this reduced warming could still imply substantial cost savings due to avoided monetary and physical damages not represented in this study. For example, small temperature differentials could help securing the future of coral reefs that provide crucial ecosystem services (Schleussner *et al* 2016).

We observe most substantial risk increases for economic costs: a doubling of long-term costs and a tripling of short-term costs. This is due to the much smaller CO_2 budget for the 1.5 °C target that requires even deeper reductions in residudal fossil fuel emissions and a much greater reliance on carbon dioxide removal (supplementary figure S6) to pull temperatures back to 1.5 °C by 2100 after a brief period of overshoot (Rogelj *et al* 2015). For indicators related to fertilizer use, food and energy prices, CCS and nuclear, risks increase only incrementally. This is partly due to assumed maximum deployment levels that are already reached under the 2 °C scenario. For example, yearly carbon sequestration of carbon dioxide into geological reservoirs is constrained by a certain fraction of total reservoir capacity, and this constraint is already binding in later decades in the 2 °C scenario. Therefore, total CCS storage can only be increased by accelerating the ramp-up of this technology.

Dedicated sustainabilty policies can reduce impacts along many dimensions, and compensate incremental risks of 1.5 °C

Given the widespread concerns with regard to particular sustainability risks of mitigation (Jakob and Steckel 2016, Stechow *et al* 2016), the key question is whether and how risks (reductions) and benefits (amplification) can be directly managed through dedicated policies. This is particularly important as risks and opportunities are more significant under 1.5 °C than 2 °C scenarios (figure 2). Hence, can the additional sustainability risks of 1.5 °C scenarios be reduced or offset through the combined package of dedicated policies?

The combined additional policies we consider here (the impact of individual policy components are discussed below) have a substantially positive impact in all sustainability indicators with the exception of short term costs, strongly boosting the benefits, and alleviating most risks considerably. In all four indicators where default mitigation policies already result in a benefit, the additional benefit from the sustainability policies is higher than the improvement from moving from 2 °C to 1.5 °C. For fertilizer use and food prices, the additional policies even fully offset the sustainability risks of mitigation implied by pricing policies, resulting in a benefit of reducing fertilizer use by one quarter and food price increases even by three quarters compared to the baseline.

For some policy risk indicators, a certain risk level remains even with the targeted sustainability policies. For four of these indicators, however, energy prices, bioenergy cropland, long-term costs and geological storage requirement, the additional sustainability policies more than offset the risk difference between the 2 °C and the 1.5 °C scenario, leading to considerably lower risks in 1.5 °C_Sust relative to the 2 °C_Def.

Our analysis nevertheless shows that the better attainment of a broad set of sustainability targets comes at the price of increased short-term costs. Yet the interpretation of this trade-off is complicated by the set of underlying value judgements. First, stakeholders place differing value weights on each dimension, rendering their comparison problematic outside of a procedural setting (Edenhofer and Minx 2014, Edenhofer and Kowarsch 2015, Kowarsch *et al* 2017). In this sense, strengthened (and costly) mitigation ambition may be judged as appropriate—particularly once the costs of inaction (and the potential range of additional benefits) are credited.

It is important to note again that these costs do not take into account any avoided damages due to lower temperature increase nor monetary benefits from reduction in other externalities like air pollution. Second, there is a trade-off between costs incurred in the first half of the century vs. costs later on. Underlying the optimization that leads to the temporal profile of mitigation costs in the default scenarios (with higher relative costs in later decades) is a pure rate of time preference of 3%. There is a lively debate around whether or not lower rates at least for later periods would be called for from an intergenerational justice point of view (which would favour more balanced profiles like in the Sustainable scenarios). From a sustainability perspective, it would be important to explore to what extent higher consumption losses in the near-term will impact on poverty reduction. However, since our modeling system does not differentiate within-region income classes, such an examination is outside the scope of our analysis.

Complementarity of individual sustainability policy approaches due to different risk profiles

An analysis of the individual effects of the components of the sustainable policy package (table 1) shows that they have significant complementarity, such that their combination performs best in terms of alleviating sustainability risks of mitigation and enhancing benefits (figure 3).

The first policy package ('_regul') consists of direct regulation of a range of controversial technologies and management practices in both the energy and land-use systems, as well as standards supporting more sustainable alternatives. Figure 3(*a*) shows how this package of policies impacts the overall sustainability assessment under 1.5 °C policies.

Five of the indicators, water withdrawal, uranium and CCS deployment, nitrogen use and land for bioenergy crops directly show the desired effect of the regulation. In the temperature and SO_2 indicators, this policy package also shows a slight benefit, which is mainly due to the reduced reliance on CCS, which in turn leads to somewhat higher carbon prices and thus slighty faster decarbonization. In the socio-economic indicators, however, clear trade-offs emerge. While the adverse effect on food prices and long-term costs is very small, short term economy-wide costs increase by more than 50% due to the regulation.

The second policy package ('_early'), increased early action, shifts the mitigation burden in time, by introducing a higher initial carbon price increasing exponentially at a rate of 3% p.a. compared to the 5% p.a. increase in the default policy scenarios. Therefore, short-term costs are higher, but long-term costs lower than in the default case. Additionally, faster retirement of existing capacity is allowed, and the carbon price applied in the land-use system is halved, which leads to less afforestation (supplementary figure S6) and negative emissions in the long run and thus further reduces near-term emissions.

The primary impact of this policy package is a faster phase-out of fossil fuels in many sectors, which is mirrored in lower 2050 temperatures and the SO_2 indicator which is nearly halved in comparison to the default 1.5 °C scenario. Nuclear use is expanded faster in the near-term to make up for the faster phase-out of fossil fuels, giving rise to increased proliferation related risks. Enhanced early action limits long-term mitigation pressures, and therefore results in a reduction of

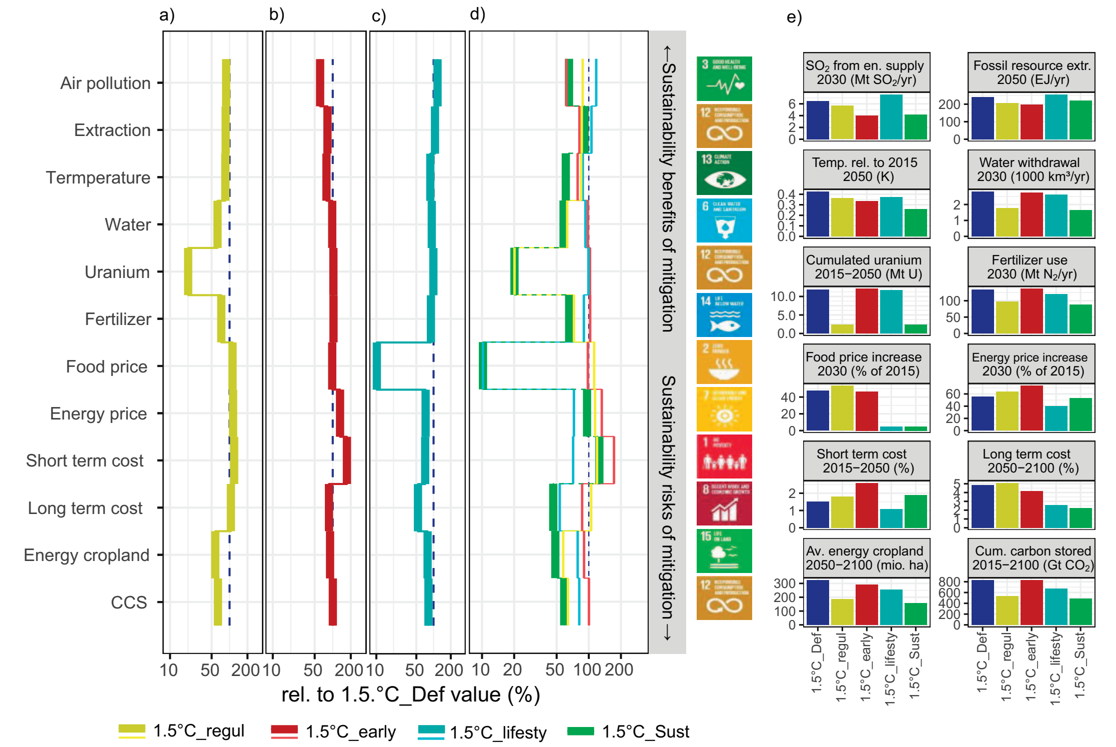

Figure 3. Detailed comparison of individual policy approaches. Sustainability indicators for five different 1.5 °C scenarios, differentiated by policy approach. Panels (*a*)–(*d*) show relative values normalized to the 1.5°C_Ref scenario on a logarithmic scale, panel (*e*) shows absolute values and additionally indicates the time/time-span shown. All values are global totals or averages. Indicators are arranged such that the most pronounced sustainability benefits of mitigation sit on top, and the most severe sustainability risks at the bottom. This ranking is based on the relative values, and does not imply a normative weighting of the different dimensions which can only emerge from broad public deliberations.

cropland required for bioenergy in the 2nd half of the century. The main trade-off resulting from early action policy package, as with the regulation, is the much increased short-term cost stemming from higher initial carbon prices (supplementary figure S7).

The third policy package ('_lifesty') consists of a promotion of less material- and energy-intensive lifestyles and healthier diets relying on fewer animal products. Such a policy reduces pressures both in the energy and land-use system, which are mutually linked via bioenergy. This leads to considerable reductions in long-term costs and food security risks. Through lower demand for fuels, mid-century temperatures and CCS requirements for negative emissions are also reduced. In contrast to the other two policy types, no stark trade-offs can be observed (with the sole exception of a 25% increase in SO_2 emissions steming from the a slower phase-out of coal power generation due to lower carbon prices). This finding suggests that lifestyle changes have a no-cost character in the climate change mitigation effort, under the assumption that welfare effects of such behavioural policies cancel out.

The previous sections have shown that individually, each of the three considered policy approaches is effective in reducing risks in some dimensions, but none manages to bring down risks across the full set of indicators considered. Furthermore, the regulation and early action packages exhibit substantial trade-offs, with especially the short-term cost indicator increasing considerably. Therefore, a combination of all three policy packages ('Sust') might be considered as a means to complement individual policies and soften their risks. Indeed, this results in the lowest risk levels in 8 out of the 12 indicators considered in figures 2 and 3. This not only applies to the 1.5 °C scenarios, but equally is valid for the 2 °C scenarios shown in figure 2 and supplementary figure S3.

Furthermore, short-term costs are, as discussed above, the only indicator in which the combined sustainability policies lead to a higher risk value than the default 1.5 °C scenario with carbon pricing alone.

Policy implications and outlook

Our results highlight the importance of synergies and trade-offs that exist between climate and non-climate sustainability dimensions. Given the inherent requirement for value judgments when it comes to weighing the different dimensions against each other, our results reinforce the call for an as broad as possible public deliberation on the exact mix of policies to take within each country (Jakob and Steckel 2016).

Crucial but unavoidable limitations of our study comprise deep uncertainties in the framing condition of the scenario analysis, both with respect to the future development of some crucial input parameters of the analysis (socio-economics, technology availability, costs and performance, etc.), as well as the structural relationship within and between the analysed systems (investments and demand for energy services, demand for agricultural products, working fundamentals of both energy and other markets, etc.). Our way of generating useful insights under these circumstances is to concentrate on the qualitative effects of analyzed policy interventions, and exploring underlying system effects.

The results highlight that the default policy scenario in the academic literature, in which mitigation is achieved by the single instrument of carbon pricing, exhibits much higher risk values in a range of sustainability indicators in comparison to other scenarios that include further sustainability measures. Yet we do not claim that in our analysis such risks remain within safe limits or sustainability thresholds even with further measures. Such an assessment would require much more fine-grained and locally-specific analysis, which we have to leave to further research. One economic standard argument for implementing climate policies via pricing only is cost-effectiveness. Accordingly the core trade-off in scenarios where sustainability risks are reduced by additional policies is higher near-term mitigation costs. To what extent avoided monetary damages associated with the sustainability risks would compensate for the higher mitigation costs is an important but challenging avenue for future research. As shown in this paper, the SDGs also provide a lens to assess climate policy, hence we see further work to design and articulate mitigation pathways in the context of human well-being, in particular focusing on food, energy and mobility provisioning—issues at the heart of an energy transformation (Lamb and Steinberger 2017).

A central insight of our study is that the benefit of dedicated sustainability policy in the considered indicators (except short-term costs and energy price) is higher than the incremental effect of moving from a 2 °C to a more stringent 1.5 °C target. Even frequently mentioned sustainability risks of mitigation like land requirement for energy crops (Fuss *et al* 2014), food prices, and nuclear and CCS deployment are much lower in a scenario reaching 1.5 °C with a sustainability policy package than reaching 2 °C with the single instrument of a global carbon price.

The analysis of different types of sustainability policies identifies their relative strengths and weaknesses. Dedicated regulation on specific risks fares best in reducing each risk individually, but typically increases pressures in other parts of the system. An increase of early action in comparison to cost-optimal policies brings down a range of risks and leads to lower mitigation costs in the long run, but results in considerably increased near-term costs. Arguments related to inter-generational equity and hedging against higher climate sensitivity values or less effective long-term mitigation might still call for such approaches. In light of complementary work on inter- and intra-national inequalities in emissions (Piketty and Chancel 2015, Rao and Min 2018) it would be an important extension to explicitly consider the impact of distributional policies which could further ease the sustainability trade-offs we discuss. Finally, we find that lifestyle changes that immediately bring down end-use energy consumption, allow for more flexibility, offsetting partially the higher short-term costs of early action.

Shifting towards healthier diets and less energy- and material-intensive consumption patterns appears to have greatest potential for reducing sustainability risks along a wide range of dimensions, although it is unclear to what extent policy-makers have a direct handle to bring about the assumed lifestyle changes and what welfare effects those would have. Certainly, shifting lifestyles would require confronting prevailing social habits, as well as the constellation of private interests that sustain, reproduce, and benefit from existing consumption patterns (Fuchs *et al* 2016). Yet such issues are also fundamental to realizing the ‘regulation’ and ‘early action’ policies directed at the fossil fuel and energy system sectors. Thus while a combination of diverse policy approaches emerges as the most promising way to balance climate and other sustainability risks, the political challenge of doing so should not be understated. A key task going forward is to explore how such policies can be adapted for local needs and circumstances, and whether they can build momentum towards a more encompassing global engagement in climate and sustainability issues.

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Annex 6

Bertram C, Luderer G, Popp A, Minx JC, Lamb WF, Stevanovic M, Humpenöder F, Giannousakis A, Kriegler E (2018) Supplementary Information

Supplementary online material for the article

Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios

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Contents

1. The REMIND-MAgPIE modeling framework

The scenarios in this study have been constructed with the coupled REMIND-MAgPIE integrated assessment modeling framework. This has been first presented in Kriegler et al. (2017), from which the following description is adapted.

The REMIND-MAgPIE integrated assessment modeling framework consists of an energy-economy-climate model (REMIND) (Bauer et al. 2008; Leimbach et al. 2010a, b, Luderer et al. 2013, 2015) coupled to a land-use model (MAgPIE) (Lotze-Campen et al. 2008; Popp et al. 2010, 2014a). REMIND (Regional Model of Investment and Development) is an energy-economy general equilibrium model linking a macro-economic growth model with a bottom-up engineering based energy system model. It covers eleven world regions, differentiates various energy carriers and technologies and represents the dynamics of economic growth and international trade (Leimbach et al. 2010a, b; Mouratiadou et al. 2016). A Ramsey-type growth model with perfect foresight serves as a macro-economic core projecting growth, savings and investments, factor incomes, energy and material demand. The energy system representation differentiates between a variety of fossil, biogenic, nuclear and renewable energy resources (Bauer et al. 2012; Pietzcker et al. 2014a; Klein et al. 2014; Pietzcker et al. 2014b; Bauer et al. 2016b, a) . The model accounts for crucial drivers of energy system inertia and path dependencies by representing full capacity vintage structure, technological learning of emergent new technologies, as well as investment mark-ups for rapidly expanding technologies. The emissions of greenhouse gases (GHGs) and air pollutants are largely represented by source and linked to activities in the energy-economic system (Strefler et al. 2014a, b). Several energy sector policies are represented explicitly (Bertram et al. 2015), including energy-sector fuel taxes and consumer subsidies (Schwanitz et al. 2014). The model also represents trade in energy resources (Bauer et al. 2015). A detailed model description can be found at http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_REMIND

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a global multi-regional economic land-use optimization model designed for scenario analysis up to the year 2100. It is a partial equilibrium model of the agricultural sector that is solved in recursive dynamic mode. The objective function of MAgPIE is the fulfilment of agricultural demand for ten world regions at minimum global costs under consideration of biophysical and socio-economic constraints. Major cost types in MAgPIE are factor requirement costs (capital, labor, fertilizer), land conversion costs, transportation costs to the closest market, investment costs for yield-increasing technological change (TC) and costs for GHG emissions in mitigation scenarios. Pricing of land-use emissions in MAgPIE includes pricing of CO_2 emissions from conversion of forest and other natural land, as well as CH_4 and $N2_O$ emissions from agriculture. In addition, the price on CO_2 emissions serves as incentive for afforestation by generating negative costs in the objective function of the model (Humpenöder et al. 2014). Biophysical inputs (0.5° resolution) for MAgPIE, such as agricultural yields, carbon densities and water availability, are derived from a dynamic global vegetation, hydrology and crop growth model, the Lund-Potsdam-Jena model for managed Land (LPJmL) (Bondeau et al. 2007; Müller and Robertson 2014). Agricultural demand includes demand for food (Bodirsky et al. 2015), feed (Weindl et al. 2015), bioenergy (Popp et al. 2011), material and seed. For meeting the demand, MAgPIE endogenously decides, based on cost-effectiveness, about intensification of agricultural production (TC), cropland expansion and production relocation (intra-regionally and inter-regionally through international trade) (Lotze-Campen et al. 2010; Schmitz et al. 2012; Dietrich et al. 2014). MAgPIE derives cell specific landuse patterns, rates of future agricultural yield increases (Dietrich et al. 2014), food commodity and bioenergy prices as well as GHG emissions from agricultural production (Popp et al. 2010; Bodirsky et al. 2012) and land-use change (Humpenöder et al. 2014; Popp et al. 2014a).

Emissions in the land-use and energy sectors are interlinked by overarching climate policy objectives and the deployment of bioenergy (Popp et al. 2014b; Rose et al. 2014; Klein et al. 2014). REMIND and MAgPIE models are coupled to establish an equilibrium of bioenergy and emissions markets in an iterative procedure (Bauer et al. 2014). The atmospheric chemistry- climate model MAGICC (Meinshausen et al. 2011) is used to evaluate the climate outcomes of the REMIND-MAgPIE emission pathways.

Code availability

The source code of REMIND can be downloaded from the PIK's webpage (https://www.pik-potsdam.de/research/sustainable-solutions/models/remind) for the purpose of reading, thus enabling transparency and review. A license that would allow further uses is currently under discussion. The website also contains links to the current documentation, including a detailed description of equations and the harmonized model documentations on the ADVANCE wiki.

MAgPIE documentation can be found at https://redmine.pik-potsdam.de/projects/magpie/wiki/MAgPIE_Version_3_-_Documentation. Additional data related to this paper may be requested from the authors. The source code is available on request for review purposes only. A license that would allow further uses is currently under discussion.

2. Additional Figures and analysis of scenario results

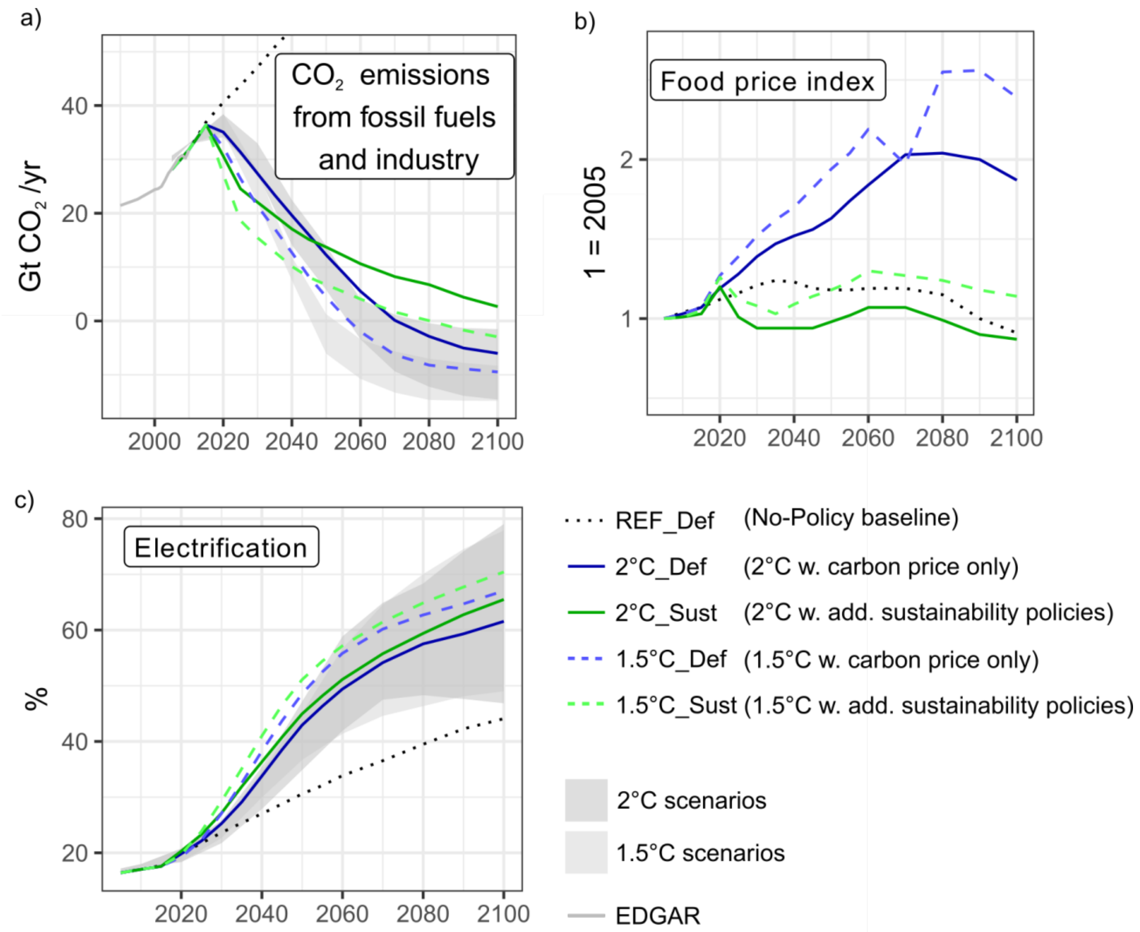

Figure S1: Further transformation characteristics in the five main scenarios. a) CO_2 emissions from fossil fuel combustion and industrial processes, b) development of the food price index, and c) electrification, shown as percentage of electricity in total final energy. Historic emission data is from EDGAR(EDGAR 2011) and the grey funnels in the background show the scenarios from previous studies on 1.5°C and 2°C scenarios(Rogelj et al. 2013; Luderer et al. 2013; Rogelj et al. 2015) selecting those scenarios with a start of ambitious climate policies in 2015 or 2020.

a)

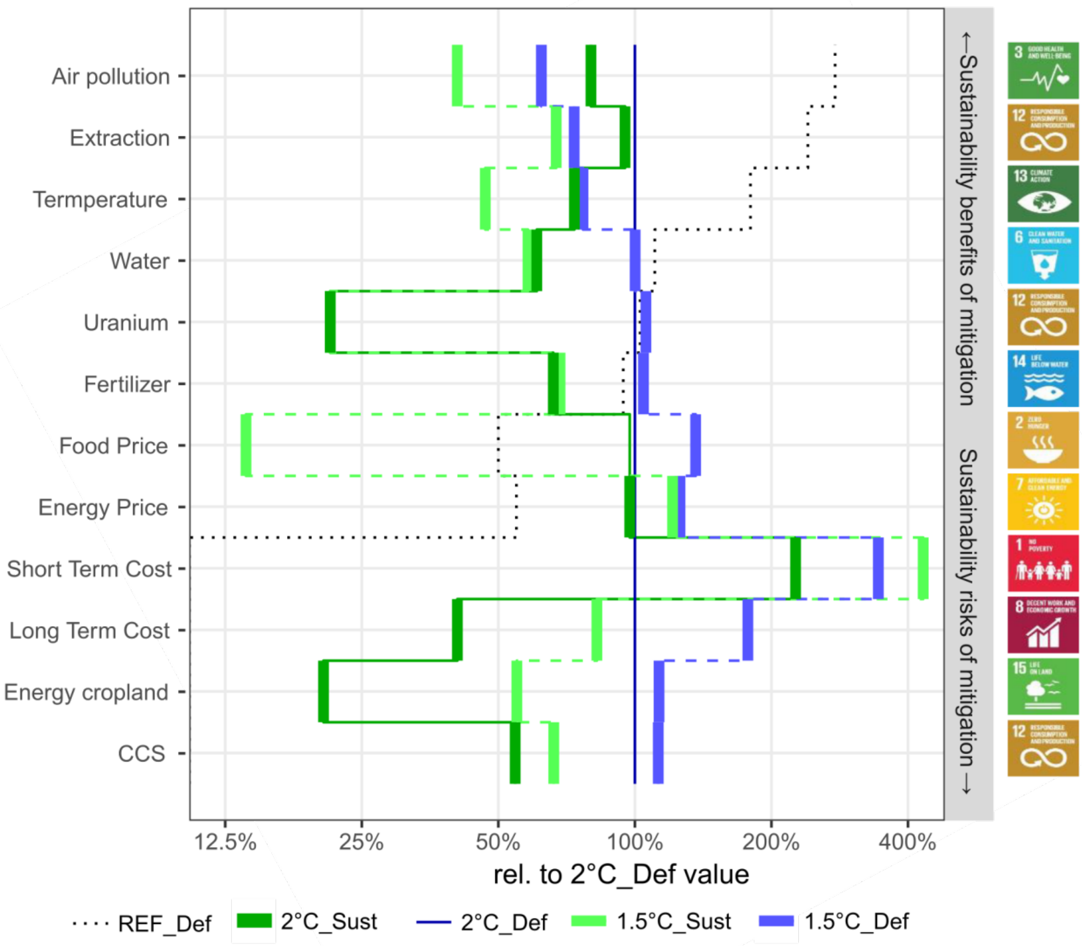

Figure S2: Version of panel a of Figure 2 of the main paper including the 2°C_Sust scenario. It shows values relative to the 2°C_Def scenario in logarithmic scale. All values are global totals or averages, times/time-spans shown can be seen in panel b of Figure 2 in the main paper. Indicators are arranged such that the most pronounced sustainability benefits of mitigation sit on top, and the most severe sustainability risks at the bottom. This ranking is based on the relative values, and does not imply a normative weighting of the different dimensions which can only emerge from broad public deliberations.

The analysis of the effect of individual policy approaches in 2°C scenarios (Figure S2) yields the same qualitative results as in 1.5°C scenarios as discussed in the main paper.

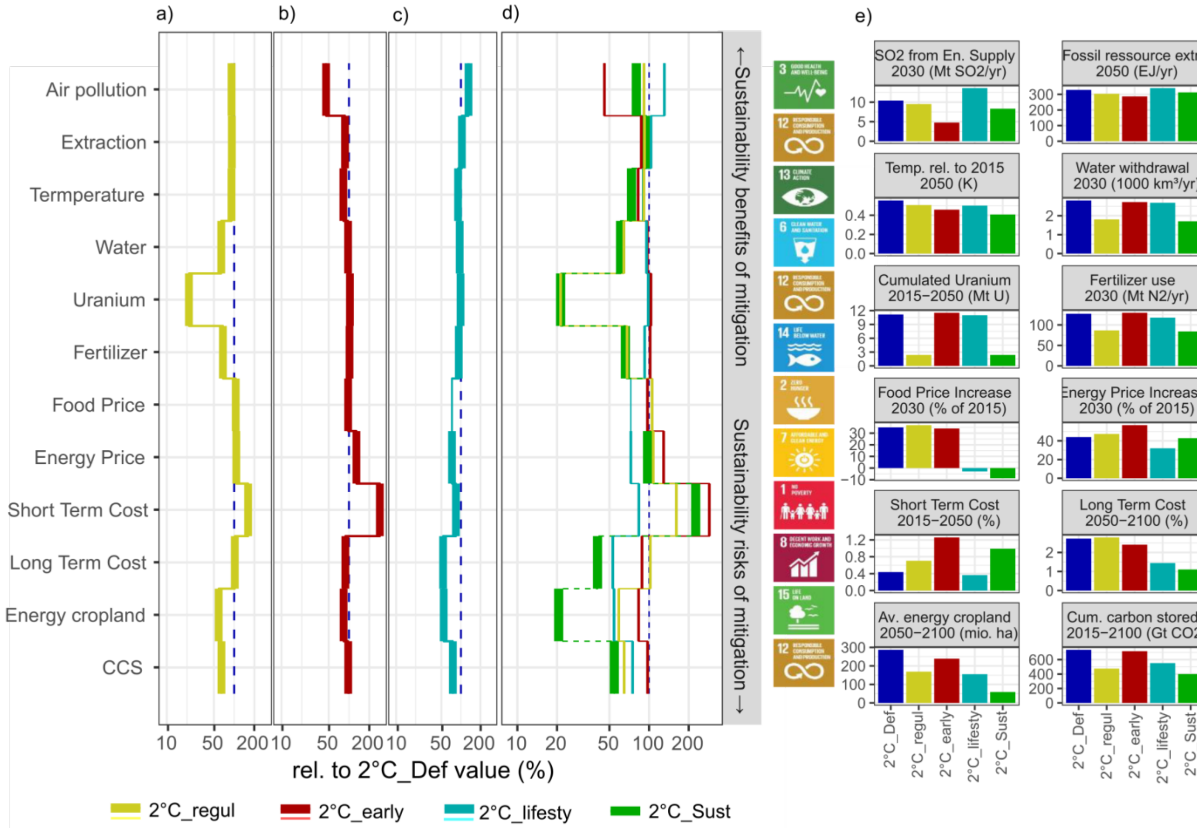

Figure S3: Detailed comparison of individual policy approaches for 2°C scenarios. Sustainability indicators for five different 2°C scenarios, differentiated by policy approach. Panel a) –d) shows relative values normalized to the 2°C_Ref scenario on a logarithmic scale, panel e) shows absolute values and additionally indicates the time/time-span shown. All values are global totals or averages. Indicators are arranged such that the most pronounced sustainability benefits of mitigation sit on top, and the most severe sustainability risks at the bottom. This ranking is based on the relative values, and does not imply a normative weighting of the different dimensions which can only emerge from broad public deliberations.

Energy and land-use system transformations

All mitigation scenarios exhibit a complete transformation of the energy sector (Figure S4). Fossil fuels remain dominant in the primary energy mix of the (counter-factual) reference scenarios without climate policies (REF_Def and REF_Sust), although renewables due to cost-reduction are projected to dominate the electricity system even in absence of climate policies. With climate policies, the expansion of renewables in the power system is much faster and fossil fuels are, with the exception of some Gas with CCS, completely eliminated at mid-century already. In the primary energy mix, the transformation is less rapid, as oil and gas both retain relevant though declining shares throughout the 21st century. Transformation is even more rapid in 1.5°C scenarios compared to 2°C scenarios. The scenarios with the sustainability policy packages are characterized by lower total primary energy and electricity inputs, as well as by considerably lower use of bioenergy and a phase-out of nuclear power. The share of nuclear power in total electricity generation also declines in all scenarios without dedicated policies, with shares dropping to below 10% in 2035 at the latest (1.5C_early), compared to a share of 10.6% in 2014 (IEA 2017).

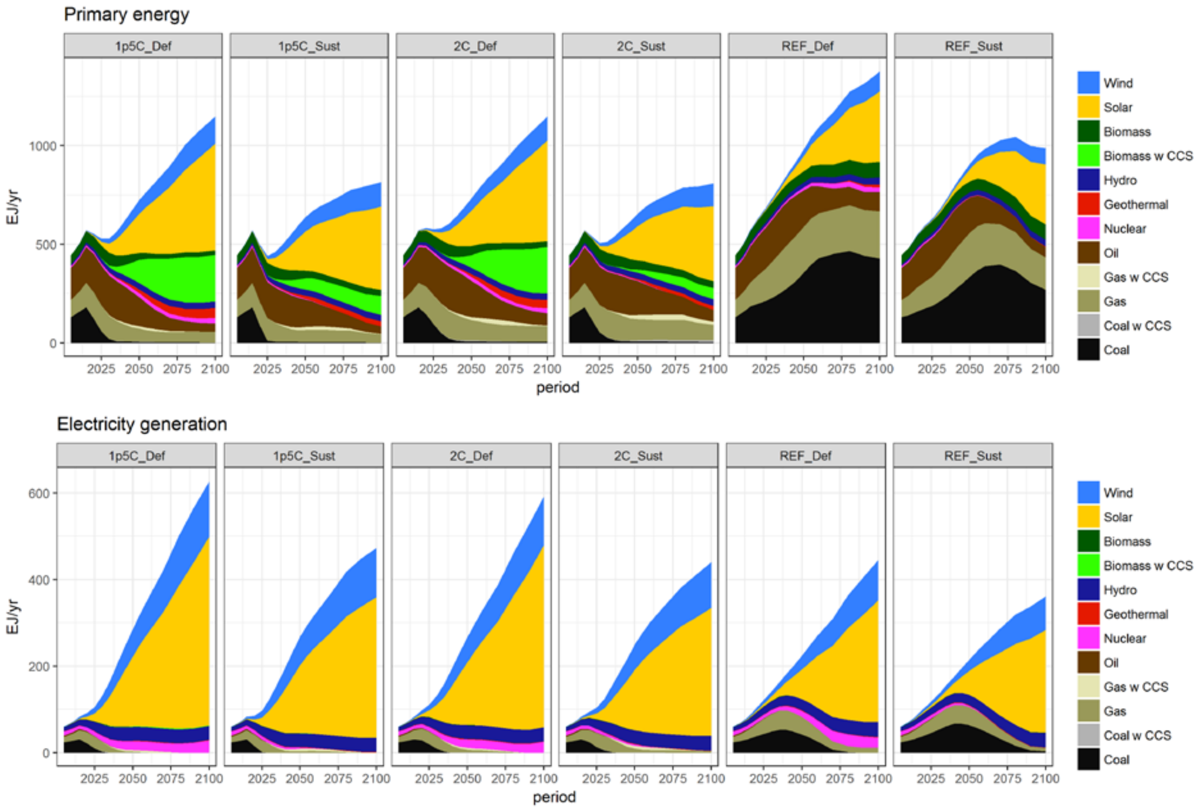

Figure S4: Energy mixes in the default and sustainability policy scenarios (Reference, 2°C and 1.5°C). The upper panel shows global primary energy mixes, the lower panel global electricity generation by technology, using direct equivalent accounting.

The change in the land-use system in the default reference scenarios (REF_Def) is given by relatively little land conversion (Figure S5): apart from the cropland expansion in about 500 million ha of pastures and 250 million ha of natural forests by 2050, there is no other land use change dynamic. Moreover, even a less dramatic land conversion happens in the reference sustainable scenario in the long run, where under a reduced consumption of animal products (lifestyle changes) no additional expansion of cropland is required. The mitigation policies encourage the land-based carbon-dioxide removal options (bioenergy with CCS and afforestation) and trigger a larger transformation in the land-use system. While there is a considerable pressure on cropland, and consequently on agricultural production, in the default mitigation scenarios (1.5°C_Def and 2°C_Def) compared to the cropland requirements in the REF_Def scenario, the constant cropland area in the sustainable scenarios gives more opportunity for afforestation on land that has much larger potential for atmospheric CO_2 sequestration. Therefore, the sustainable mitigation scenarios are characterized by more afforestation areas than what is the case for the default mitigation scenarios.

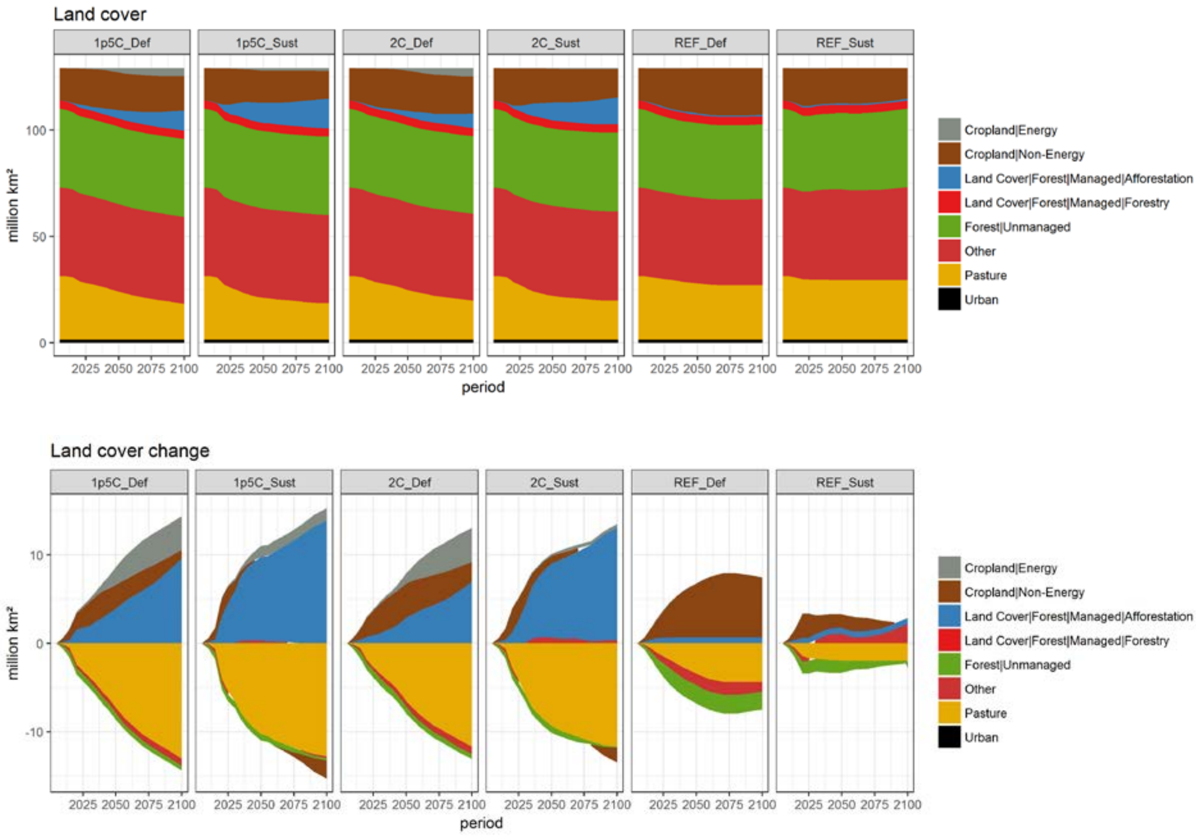

Figure S5: Composition of global land cover (upper panel) in the default and sustainability policy scenarios (Reference, 2°C and 1.5°C), and land cover changes (lower panel). 1 million km² equals 100 million ha.

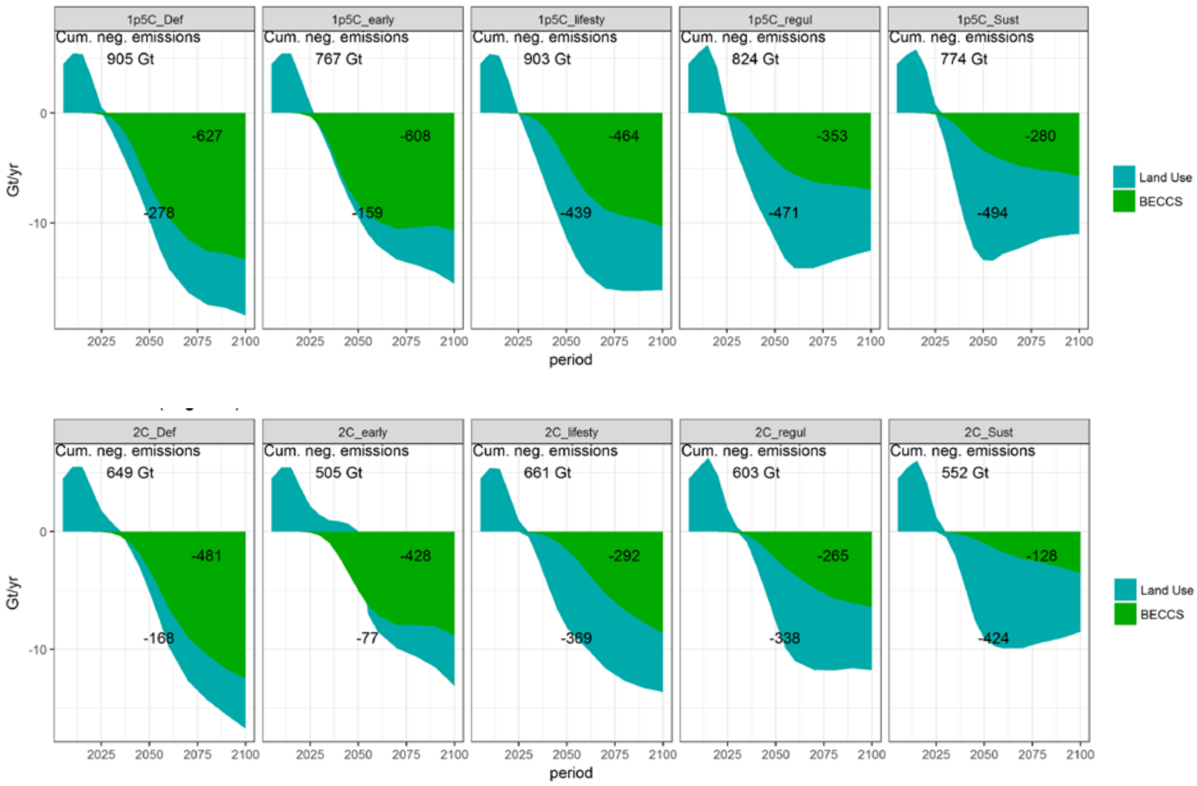

Figure S6: Land-based anthropogenic emissions in all 10 mitigation scenarios. Positive land-use emissions (land source) come from various land conversion and management processes, whereas the negative contributions labelled "Land Use" exclusively come from afforestation.

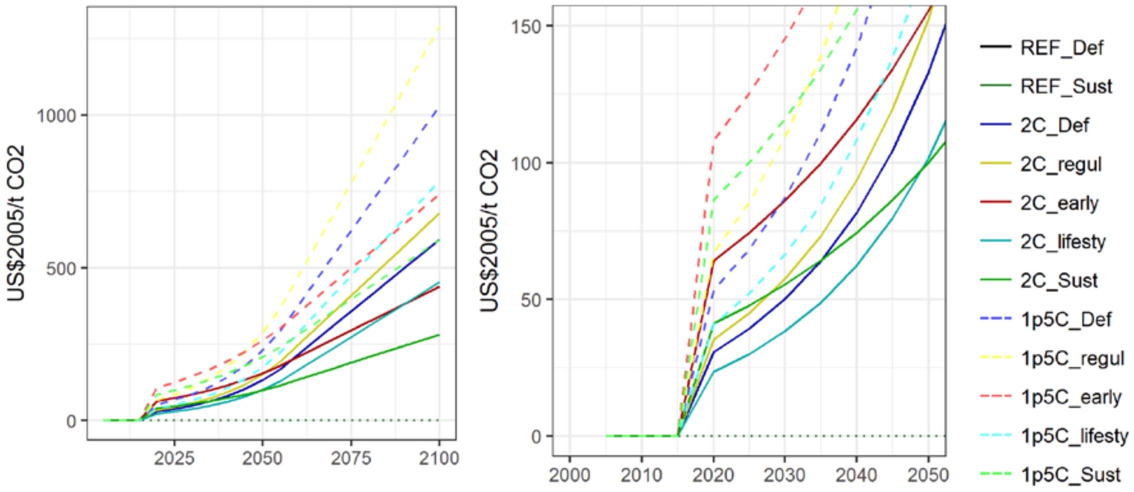

Figure S7: Carbon prices in the policy scenarios. Panel a) shows the trajectories over the full 21st century, panel b) zooms into the first half to better make out the differences in initial carbon price values in 2020 and the next decades. Please note that these are the carbon prices applied to the energy system in REMIND.

3. Description of policy scenarios

Choice of measures and grouping into scenarios

The construction of additional policy measures followed a three-fold motivation: first, measures should plausibly lead to a relevant improvement of one of the sustainability aspects related to mitigation; second, they necessarily need to be able to be represented in a meaningful way in our modeling framework, and thirdly, an implementation appears to be realistic at least in some jurisdictions (although it is clear that the assumptions of globally homogeneous policies is a unrealistic simplifying assumptions that we make in order to have an easily understandable and transparent scenario setup and clearly contrasted scenarios).

The motivation for not only considering the combined impact of all additional measures but also analyzing three additional scenarios with subsets of these measures installed (“Regulation”, “Early action”, “Lifestyle”), is to better understand the working mechanisms and identify potential trade-offs. As shown in the last result section of the main paper, more trade-offs can be detected as the combination of all policy approaches masks some of these.

We group measures with similar characteristics, although the implementation mechanism differs also within policy groups. The perhaps unintuitive allocation of the halved land-use carbon price stems from the fact that the main effect of such a policy is that more near-term mitigation happens, as the incentive for afforestation and the negative emissions this offers in the long-term is reduced. On the other hand, a real-world policy argument for such a policy is that carbon stored in fossil fuels has a different characteristic compared to carbon storied in vegetation and soils, as for the latter the question of permanence is much less clear.

Cost considerations within the scenario implementation and analysis

Substantial part of the analysis relates to the economics of the scenarios. For the alternative policy settings in targeted policy scenarios in the REMIND and MAgPIE models, we do not consider the explicit costs for implementation of each of the proposed measures. For measures implemented as an additional constraint in the model however (water, forest, nuclear, CCS, and electric vehicles policy), an indirect cost of having fewer options emerges endogenously. In contrast, the assumption of increased retirement potential in REMIND widens the solution space of the model.

A special case are the assumptions on reduced demand for energy and food, especially livestock products. They are implemented through recalibrating the demands, which means that the costs (in terms of reduced welfare) are not represented. On the other hand, clear monetary benefits of such lifestyle shifts (e.g. through reduced health system costs due to more active life-styles and healthier diets, or reduced costs of congestion and accidents) are also not taken into account, and the question on the balance of this two counteracting forces is open.

In some policy cases (trade liberalization, 1st generation biofuel phase-out) removal of barriers or other distortive economic instruments would come in practice at no substantial costs. Other policy cases (water and forest protection) would require limited monitoring costs which are not represented, but have a strong impact by bounding cropland expansion and production under irrigated agriculture and therefore increase agricultural production costs. Further, the costs for agricultural demand management are not necessarily high (e.g. educational policy costs, regulation of market transparencies and advertising, etc.) when aiming at a behavioural change, but concurrently such a policy can also have benefits with governmental health policies, thus reducing fiscal spending. Finally, other agricultural management measures (agricultural waste and improvements in nitrogen use efficiency) would require additional monetary spending and substantial transaction costs for the desired change in management to be accomplished and therefore could slightly change the outcomes obtained in the regulation and sustainability package policy scenarios presented here.

4. Description of indicators

At the core of the analysis is the multi-dimensional comparison of the different long-term targets and policy paradigms along a set of sustainability indicators presented in Table 2 of the main paper. The indicators each represent global stressors, which ceteris paribus make an achievement of the connected SDG (right column of Table 2) more difficult, and which can be meaningfully compared in an explorative scenario analysis as ours. In each case, there are various processes that also influence the achievement of the respective SDG target which are not modelled.

The global indicator framework of the Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs) (Statistical Commission pertaining to the 2030 Agenda for Sustainable Development 2017) is not suitable for our purpose, as its purpose is to define indicators which enable a real-time tracking of progress towards achievement of the goals until 2030, whereas we perform a comparative scenario evaluation for the time frame 2030-2050 and beyond. Our analysis thus goes beyond also the SDG time frame. We thus connect the indicator of carbon storage with SDG 12, although carbon storage itself is not at all considered within the SDG framework which is explained by the fact that carbon storage is practically not existent until now, and will also not be a defining issue of overall sustainability until 2030. In deep decarbonisation scenarios as considered here, however, the issue of carbon storage will be of high importance and can be best situated in goal 12 out of the 17 SDGs, as suitable reservoirs for storage are limited, and the issue of permanence also calls for a cautious use of this technology.

In the following, the details of the indicators are presented.

SO_2 emissions from power generation

This indicator is chosen to represent the air pollution dimension of the scenarios. While other species and SO_2 from other sources also have an important role on the total burden of air pollution, this variable was chosen as the different policies here lead to very different outcomes already in the short term and qualitatively the results for other species are comparable. We show the values in the year 2030.

Fossil fuel extraction

The extraction of fossil fuel resources at a time-scale orders of magnitudes shorter than required for their built-up is not only problematic from a climate change point of view. If fuels get burnt, it means that less of this fuels are available for feedstock in the chemical industry, but also that huge amounts of material get mobilized, including harmful substances.

2050 Temperature

The temperature trajectory resulting from the modeled emission trajectories in the different scenarios is calculated using the reduced-form climate model MAGICC (Model for Greenhouse gas Induced Climate Change) (Meinshausen et al. 2011). Adverse impacts from climate change and ocean acidification are not only determined by the long-term warming level, but also the medium-term warming induced by near to medium term emissions. This indicator is meant to complement the long-term warming target which is prescribed by exogenous carbon budgets. The mid-term warming indicator shows the increase in 2050 relative to 2015. Temperature increase relative to pre-industrial is ~1°C higher, as warming in 2015 is reported at ~ 1°C above pre-industrial.

Water withdrawal for irrigation and energy

This indicator is a summation of water withdrawal for irrigation of both crop and energy plantations, as well as for cooling purposes in power generation. While only a regionalized analysis would be able to directly analyze water scarcity, this indicator is a proxy in our framework. We show values for the year 2030.

Fertilizer use

To illustrate the near-term effect of policies on the nitrogen cycle we show the values in the year 2030.

Cumulative uranium extraction

A range of risks are associated with nuclear power use: ionizing radiation from uranium mining, safety risks inherent to nuclear power plant operation, security risk related to proliferation (which additionally implies a link to SDG 16 “Peace and justice and strong institutions”), and long-term risks of nuclear waste disposal. These risks are included in the indicator- cumulative uranium extraction from 2015-2100, calculating by interpolating linearly between the 5-year (-2060) and 10-year time steps.

Food price index

As an indicator of changes in food commodity prices, we analyse a chained Laspeyres price index that weights prices based on food baskets in the previous period. Food baskets are defined on exogenous regional demand. We show values for the year 2030, indexed to 2015 levels.

Energy price index

As an indicator of changes in energy prices, we analyse a chained Laspeyres price index that weights prices based on energy baskets in the previous period. Energy baskets emerge endogeneously, as input to the macro-economic production function. We show values for the year 2030, indexed to 2015 levels.

Short-term costs

In our scenarios, we do not represent losses from climate damages. Therefore, deviation through climate and sustainability policies from the no-policy baseline by design leads to lower consumption. The consumption difference between each policy scenario and the respective no-policy baseline (REF_Def and REF_Sust) is called consumption loss. The consumption in scenarios calibrated to different exogeneous demand trajectors ("lifesty" and "Sust") cannot be directly compared to the default baseline, therefore for these scenarios a separate baseline (REF_Sust) is used to determine the cost indicators.
As short-term cost, we then define the cumulative consumption loss from 2015-2050, discounted at 3%, and expressed relative to the cumulative consumption in the respective baseline over the same period, again with 3% discounting. Importantly, these costs do not take into account avoided damages due to lower warming or any monetarization of other feedbacks (through air pollution, reduced health expenditures, etc.). We link this indicator to SDG1, as near-term eradication of poverty is most directly hit by this near-term costs. It is clear however, that a comprehensive analysis of poverty requires more detailed modeling of different income groups which is beyond the scope of our paper.

Long-term costs

This indicator is calculated in the same way as short-term costs, only considering the period 2050-2100. We link this indicator to SDG 8, as long-term economic effects do relate to the underlying topic of finding sustainable growth path for the economies. It is clear however, that the simplified growth core of our modeling does not address many of the challenges for long-term growth.

Energy cropland

A major concern with mitigation scenarios, that has often and prominently been raised is the land requirement for energy crops. Potential risks relate to competition for food crops (which is partly reflected also in our food price indicator), issues of land rights, but also biodiversity. We show the average of cropland area from 2050-2100.

Cumulative sequestered CO_2

The risks associated with the geological sequestration of CO2 are shown as cumulative sequestered carbon from 2015-2100, interpolating linearly between the 5-year (till 2060) and 10-year (2060-2100) time steps.

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