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

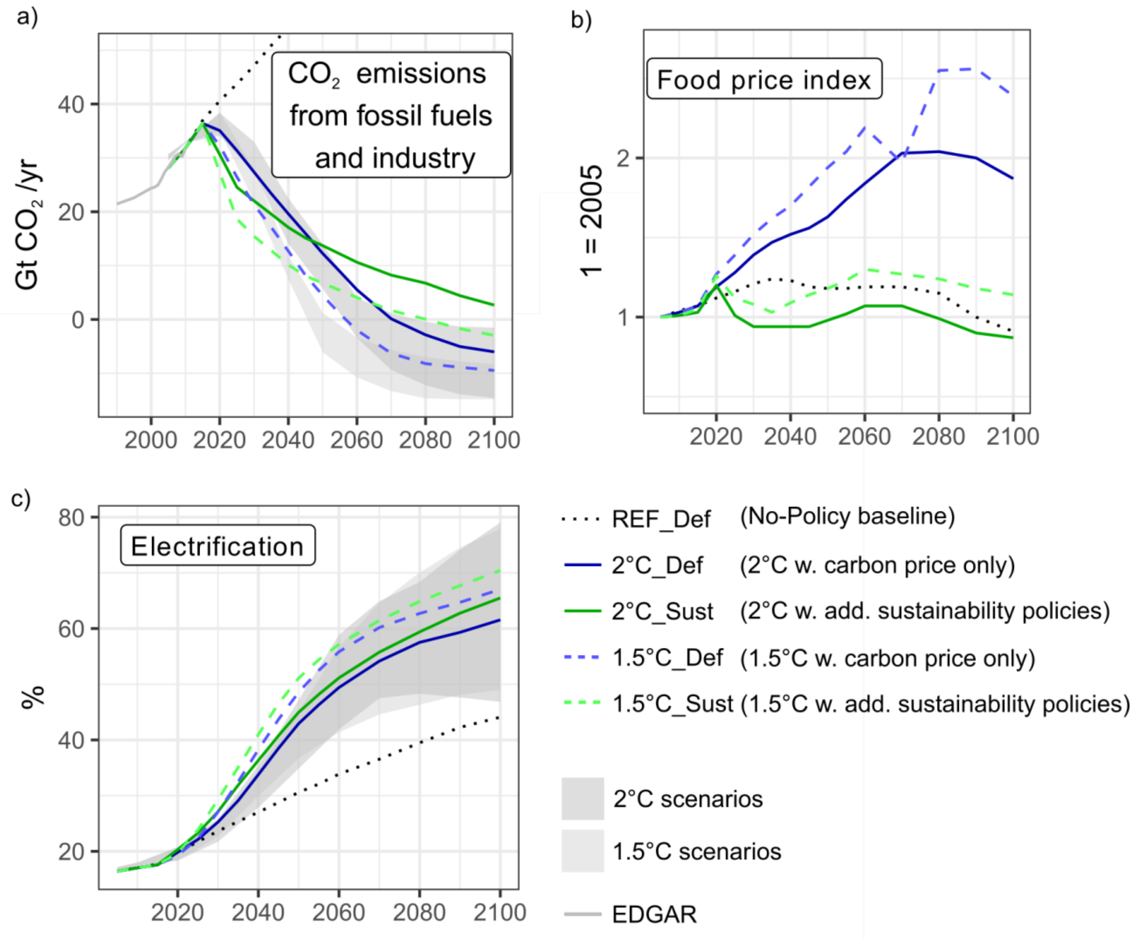

Figure S1: Further transformation characteristics in the five main scenarios. a) CO_2 emissions from fossil fuel combustion and industrial processes, b) development of the food price index, and c) electrification, shown as percentage of electricity in total final energy. Historic emission data is from 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.

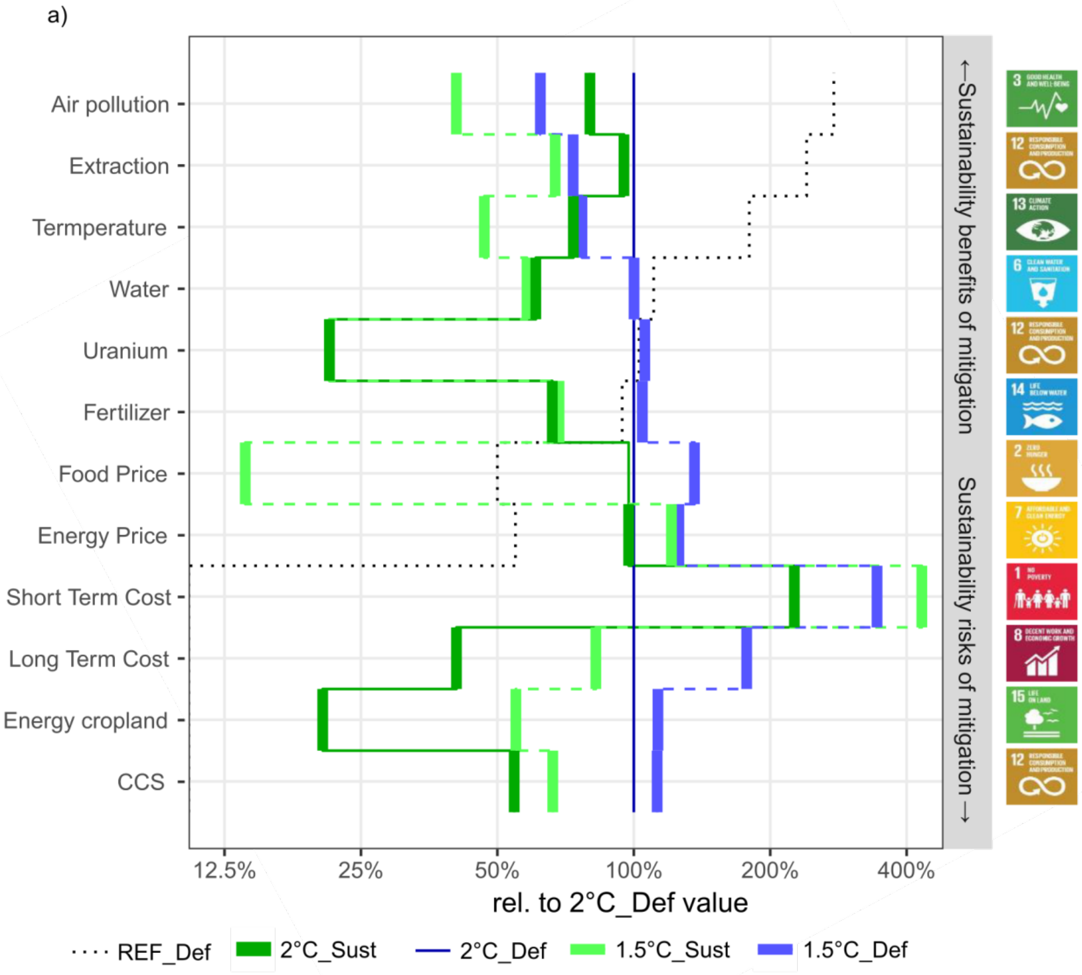

Figure S2: Version of panel a of Figure 2 of the main paper including the 2°C_Sust scenario. It shows values relative to the 2°C_Def scenario in logarithmic scale. All values are global totals or averages, times/time-spans shown can be seen in panel b of Figure 2 in the main paper. Indicators are arranged 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.

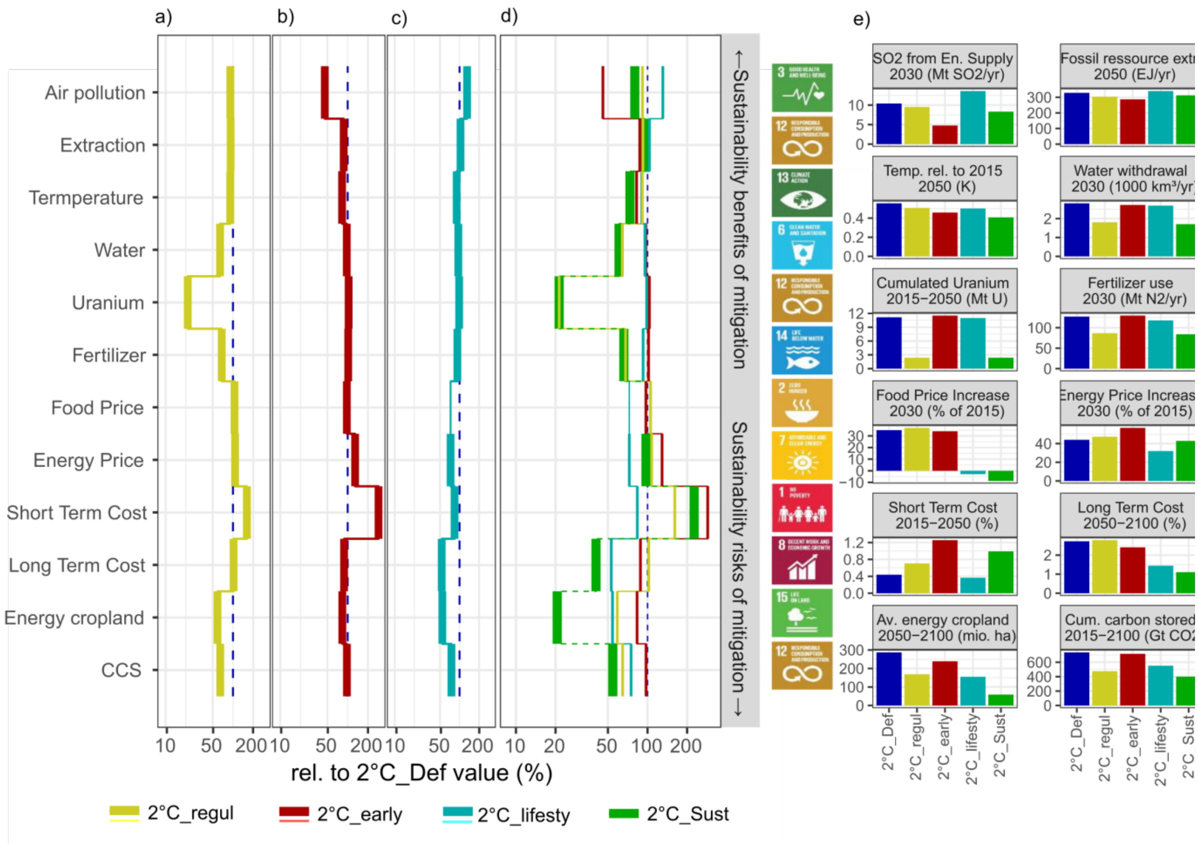

Figure S3: Detailed comparison of individual policy approaches for 2°C scenarios. Sustainability indicators for five different 2°C scenarios, differentiated by policy approach. Panel a) –d) shows relative values normalized to the 2°C_Ref scenario on a logarithmic scale, panel e) shows absolute values 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).

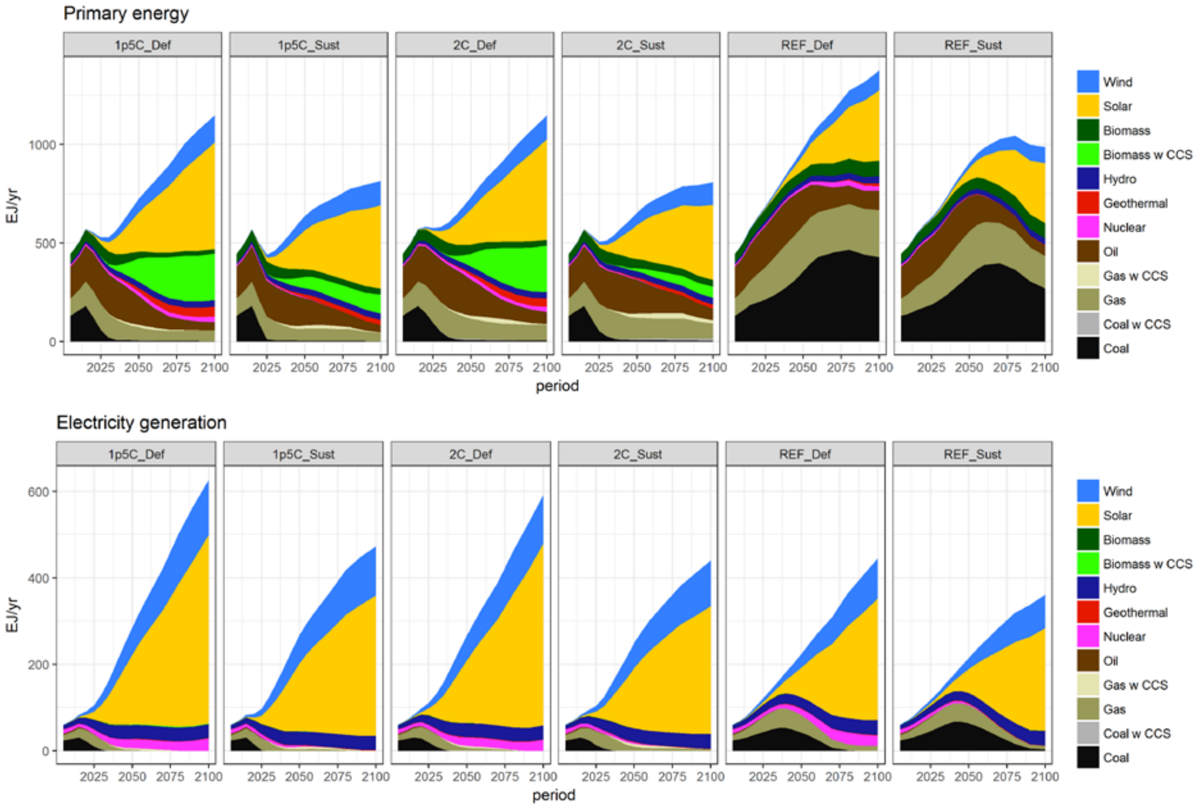

Figure S4: Energy mixes in the default and sustainability policy scenarios (Reference, 2°C and 1.5°C). The upper panel shows global primary energy mixes, the lower panel global electricity generation by technology, using direct equivalent accounting.

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.

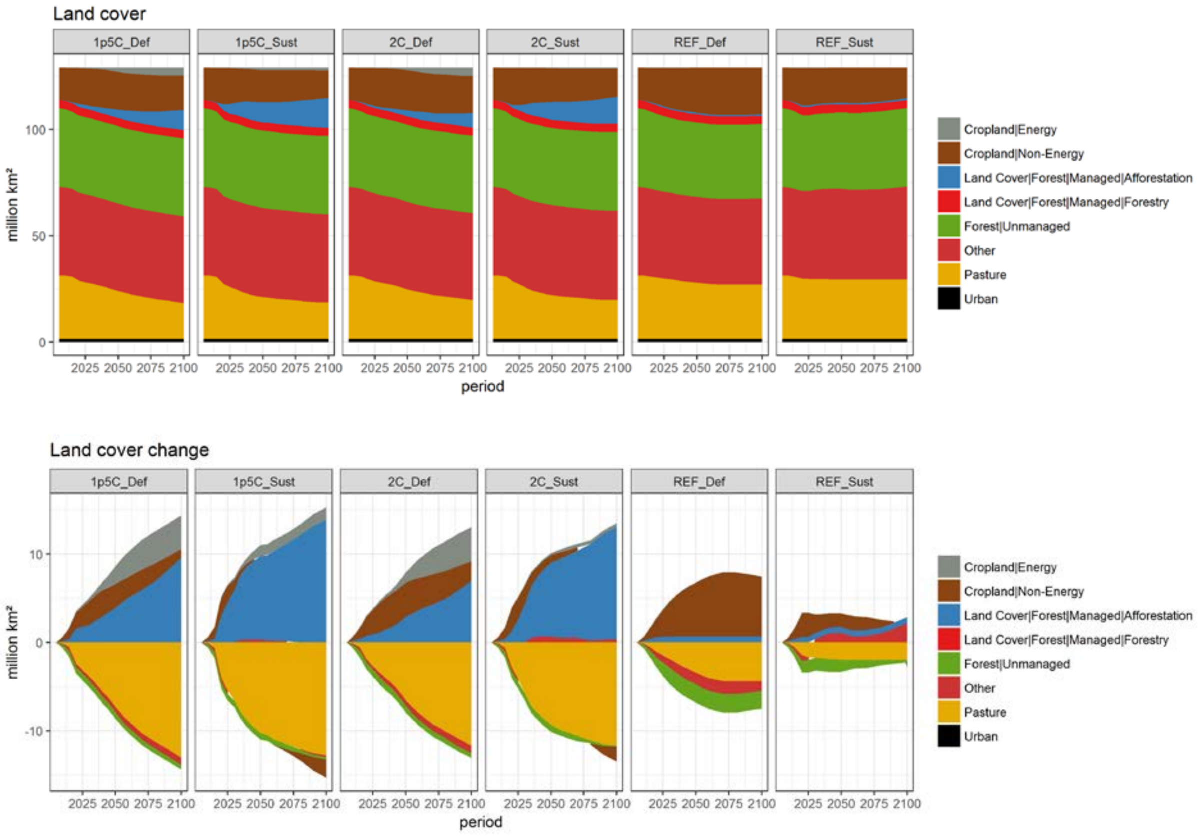

Figure S5: Composition of global land cover (upper panel) in the default and sustainability policy scenarios (Reference, 2°C and 1.5°C), and land cover changes (lower panel). 1 million km² equals 100 million ha.

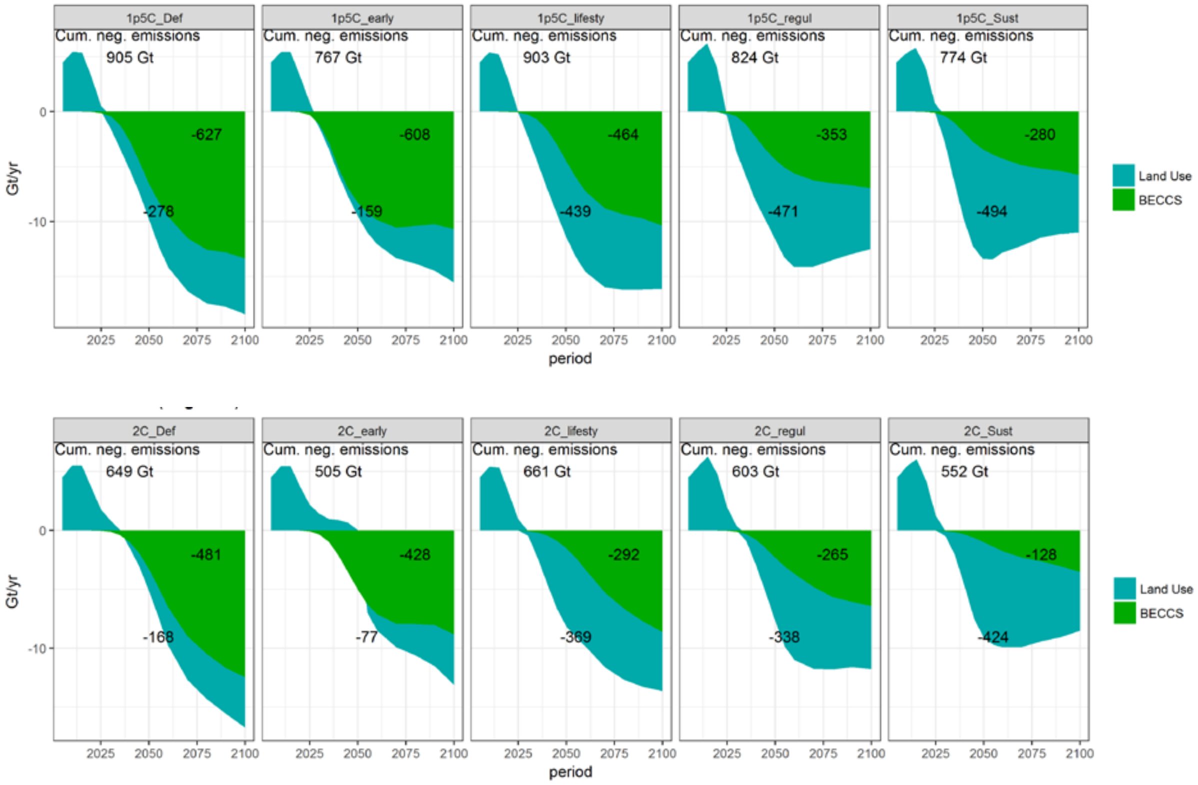

Figure S6: Land-based anthropogenic emissions in all 10 mitigation scenarios. Positive land-use emissions (land source) come from various land conversion and management processes, whereas the negative contributions labelled “Land Use” exclusively come from afforestation.

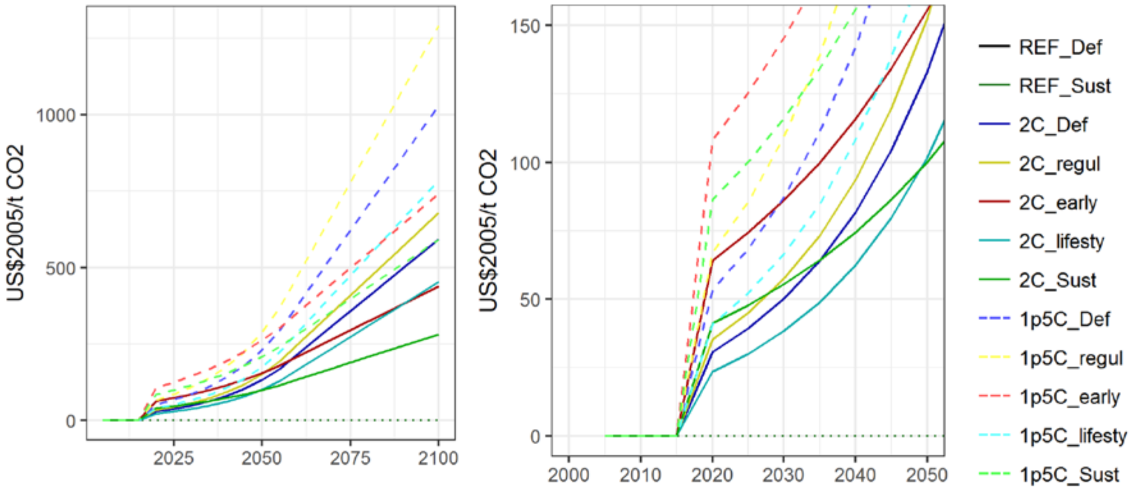

Figure S7: Carbon prices in the policy scenarios. Panel a) shows the trajectories over the full 21st century, panel b) zooms into the first half to better make out the differences in initial carbon price values in 2020 and the next decades. Please note that these are the carbon prices applied to the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