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Assessing synergies and trade-offs of diverging Paris-compliant mitigation strategies with long-term SDG objectives

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ABSTRACT

The Sustainable Development Goals (SDGs) and the Paris Agreement are the two transformative agendas, which set the benchmarks for nations to address urgent social, economic and environmental challenges. Aside from setting long-term goals, the pathways followed by nations will involve a series of synergies and trade-offs both between and within these agendas. Since it will not be possible to optimise across the 17 SDGs while simultaneously transitioning to low-carbon societies, it will be necessary to implement policies to address the most critical aspects of the agendas and understand the implications for the other dimensions. Here, we rely on a modelling exercise to analyse the long-term implications of a variety of Paris-compliant mitigation strategies suggested in the recent scientific literature on multiple dimensions of the SDG Agenda. The strategies included rely on technological solutions such as renewable energy deployment or carbon capture and storage, nature-based solutions such as afforestation and behavioural changes in the demand side. Results for a selection of energy-environment SDGs suggest that some mitigation pathways could have negative implications on food and water prices, forest cover and increase pressure on water resources depending on the strategy followed, while renewable energy shares, household energy costs, ambient air pollution and yield impacts could be improved simultaneously while reducing greenhouse gas emissions. Overall, results indicate that promoting changes in the demand side could be beneficial to limit potential trade-offs.

1. Introduction

Along with the Paris Agreement, which aims to hold the average global temperature increase to "well below 2 °C" (UNFCCC, 2015), the Sustainable Development Goals (SDG) Agenda is increasingly becoming a framework around which international development institutions can benchmark their goals. It is becoming increasingly necessary to provide policymakers with useful tools to show how specific policy interventions will contribute to, or exacerbate, the ability of different sectors to support country or region-wide sustainable development pathways. SDGs targeted to 2030, both at national and at global level, could potentially be affected by the level of compliance of domestic GHG emission reduction commitments by signatory countries of the Paris Agreement, via their Nationally Determined Contributions (NDCs), which are also focused on 2030 in most cases. Previous studies of SDG interactions suggest that it is likely that synergies outnumber trade-offs (IPCC, 2018; Nilsson et al., 2018; Pradhan et al., 2017), serving as an incentive for policymakers to look for alliances outside their sectors and increase development outcomes. The nature of these interactions will have different temporal and geographical scales (Kroll et al., 2019; Warchold et al., 2021) so interventions should be designed considering different time frames and regional contexts.

Despite being formulated as overarching and indivisible, the presentation of the SDGs as individual elements risks a siloed policy implementation approach, reflecting traditional strategies within government institutions (ICSU and ISSC, 2015). If the goals were independent of each other, it would suffice to pursue each goal individually to achieve an overarching sustainable development goal (Costanza et al.,

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2016). However, designing policies targeting one specific sector may result in lock-in effects and diverging impacts across other sectors hindering the fulfilment of the sustainable development agenda (Anderson et al., 2021; Le Blanc, 2015; Pradhan et al., 2017). Systems-based approaches that acknowledge the interactions and interconnections between the economic, environmental and social pillars and aim to firstly identify and then balance synergies and trade-offs across these pillars are urgently needed. There is a need for integrative approaches to support national development planning for SDGs and identify anticipated plausible consequences of different policy interventions.

The need for such an approach has become evident under the exceptional circumstances of the covid-19 pandemic, where greenhouse gas (GHG) emissions were temporarily reduced due to lockdowns in many advanced economies (Le Quéré et al., 2020; Liu et al., 2020). However, that happened at the expense of an economic crisis and increasing unemployment, directly risking a whole range of other SDGs concerned with decent work, economic growth, and reduced inequalities. This is not a desired scenario and calls for widening the perspective and addressing the 17 SDGs in an integrated and indivisible manner. The pandemic has jeopardised the progress towards the 2030 Agenda (Nature Editorial Board, 2020), but at the same time lessons learned during this unprecedented situation open a window of opportunity to rethink sustainable transformation plans (Pradhan et al., 2021).

Integrated Assessment Models (IAMs) have been extensively used to analyse interconnections within nexus approaches (TWI2050, 2018; van Soest et al., 2019). IAMs offer a holistic vision on specific aspects earth-human interactions by combining scientific knowledge on different domains such as energy, water use, land use and climate systems. They have been criticised for lacking transparency in their process, for relying excessively on insufficiently explored technological solutions (Gambhir et al., 2019) and for not considering social dynamics such as policy efficacy or distributional impacts which can affect the social acceptability of the decarbonisation plans (Peng et al., 2021). They are nonetheless proving to be critically important to analyse the impact of combinations of mitigation and adaptation policies and to account for uncertainties and potential linkages between resources (Skaggs et al., 2012).

This study applies an integrated modelling framework to highlight the global and regional SDG interactions which could arise in the mid- and long-term from pathways relying on different mitigation alternatives when pursuing the Paris Agreement. The exploration of SDG interactions with mitigation scenarios that are highly reliant on either behavioural changes, technological deployments or nature-based solutions for mitigation is a novel area of research that reveals insights into how a biased focus on solutions coming from the supply side might exacerbate SDG trade-offs.

The rest of the paper is set out as follows: Section 2 provides an overview of previous work analysing SDG interactions with a nexus perspective both from qualitative and quantitative approaches. Section 3 then covers the explanation of the modelling tools used, the assumptions behind the mitigation scenarios designed and the SDG impacts analysed. Section 4 lays down the SDG impacts of each modelled scenario as well as the limitations and further research, Section 5 presents the conclusions of the study and summarises the differences in the impacts among the mitigation pathways and Section 6 unravels policy implications of the results and suggests effective policy measures inspired by recent events.

2. Existing literature on SDG interactions

Since the 2011 Bonn Nexus Conference, there is increasing consensus that nexus approaches can support integrated policymaking when dealing with complex interactions between different policy sectors (Liu et al., 2018). In particular, it is notably useful to overcome challenges of competing demands of water, food and energy arising from mitigation strategies (Müller et al., 2015). Scientific evidence suggests that current climate change trends will make it harder to reach other goals in the sustainable development agenda (Fuso Nerini et al., 2019). The Climate-Land-Energy-Water (CLEW) nexus approach aims to limit climate change impacts by looking simultaneously at the interdependencies and feedbacks of the energy, land use and water sectors (Hermann et al., 2011).

Transdisciplinary research and nexus approaches require the careful assessment of interactions and generating and sharing data across different disciplines (Fuso Nerini et al., 2018). SDGs should therefore be seen as a set of interacting cogwheels which are to be interpreted systematically for a sustainable progress "into a safe and just operating space" (Pradhan et al., 2017). Policy makers and the scientific community should engage in bilateral dialogues to integrate accurate and updated information in policy relevant studies which can help to identify priority objectives and the interactive dynamics among them.

Since the formal adoption of the SDGs in 2015, literature on empirical demonstrations of interlinkages between a significant number of goals is relatively scarce (Breuer et al., 2019). Nevertheless, several studies have focused on the interactions between SDGs and targets both with qualitative and modelling frameworks.

A few studies have examined published literature so far concerning SDG interactions, such as the global research initiative 'The World in 2050′ (TWI2050, 2018), where possible SDG compatible development pathways were examined across a set of sectors such as energy, urbanization, technology, governance, education and food security. Van Soest et al. (2019) combined a modelling expert survey with an SDG target representation and a literature synthesis of SDG coverage in IAMs to work out how interactions within the 2030 Agenda had been explored so far. Fuso Nerini et al. (2019) also examined published studies to analyse the interaction of SDG 13 – Climate Action with all the other elements of the SDG agenda. Additionally, IPCC's 1.5 °C Global Warming report analysed relevant scientific literature to show static SDG impacts at global level derived from strategies focusing on either energy supply, energy demand or land use mitigation (IPCC, 2018).

Some other studies adopted a modelling approach to explore SDG interactions in regional contexts. Allen et al. (2019) and Pedercini et al. (2018) addressed the required adjustments to national policies in place to close SDG achievement gaps in Australia and Ivory Coast respectively. Van de Ven et al. (2019) analysed the impact of land policies and technology subsidies on air pollution, energy access and GHG emissions reductions simultaneously in Eastern African countries. Liu et al. (2019) analysed multi-sectoral impacts of climate mitigation scenarios on food security, air quality, energy security and deforestation in China and Fujimori et al. (2020) focused on the Asian region and combined several models to understand the impacts of GHG emission reduction on several SDG-related sectors in scenarios aligned with temperature targets included in the Paris Agreement.

Additionally, a few modelling studies adopted a global approach. Van Vuuren et al. (2015) designed global scenarios with different combinations of technological deployments and behavioural change scenarios until 2050 necessary to simultaneously eradicate hunger, ensure universal energy, drinking water and sanitation access, reduce air pollution, limit GHG emissions and halt biodiversity loss and analysed synergies and trade-offs between them. Van Vuuren et al. (2017) compared the narratives of the Shared Socioeconomic Pathways SSP1, SSP2 and SSP3 in terms of their impact until 2100 on food consumption, energy supply and demand, air pollution, GHG emissions and land use. They also explored the implications on the energy mix and land use when transitioning from a SSP1 scenario to a scenario aligned with the climatic Paris Agreement objectives. Rogelj et al. (2018) analysed possible pathways of the five SSPs scenarios required to limit global temperature rise in 2100 to 1.5 °C and the implications on cropland availability, energy systems, GHG emissions and forest cover. Iyer et al. (2018) explored regional NDCs implications until 2030 of GHG emission reductions on food security, energy access and security, air quality, ocean acidification and land-use change. Finally, Parkinson et al. (2019)

explored the financial implications of achieving SDG 6 related targets of water access, scarcity, treatment and efficiency objectives on energy and land use pathways, while Soergel et al. (2021) examined the effects of specific coordinated sustainable development packages aimed at achieving several SDG outcomes until 2050 which include a combination of interventions on both the supply and the demand side.

Irrespective of whether they follow a global or a regional approach, the mentioned studies agree that the range and nature of the SDG impacts will depend on the specific trajectory followed for reducing GHG emissions. They either rely entirely on SSP narratives (Rogelj et al., 2018; van Vuuren et al., 2017) or assume combinations of social and technological shifts in each scenario specifically aimed at reaching predefined SDGs (Soergel et al., 2021; van Vuuren et al., 2015).

The current study aims to link the Paris Agreement and the SDGs and analyse the interactions of both agendas together and, even though, as detailed in the previous paragraphs, several modelling studies have been conducted so far to work out possible interactions among SDGs, this one constitutes a novel contribution to the literature for two main reasons. First, because it adopts both a global and a regional framework to capture dynamic transboundary effects of CLEW-related long-term SDGs derived from regional climate policies. Second, because it explores implications of the diverging decarbonisation pathways where each pathway relies on a significantly distinct mitigation narrative, achieving deep emissions cuts through either technological, nature-based or behavioural solutions. On the other hand, the authors acknowledge a more limited coverage of the SDG Agenda compared to Soergel et al. (2021) and a scenario construction with less sectoral disaggregation than van Vuuren et al. (2018) or van Vuuren et al. (2015).

For the purpose of the study, we take the definition of synergies and trade-offs as defined in the 1.5 °C Global Warming report by the IPCC (IPCC, 2018), whereby synergies and trade-offs are defined as positive and negative effects of mitigation strategies on the SDGs. We explore SDG interactions of a selection of energy-environmental SDGs deriving from a strong global reliance on one specific narrative among those, which have been put in the spotlight by recent scientific literature. Two of the identified mitigation narratives provide an important role for terrestrial ecosystems, either through the intensive use of bioenergy in combination with carbon capture and storage (CCS) to achieve negative emissions (Hanssen et al., 2020; Kriegler et al., 2013) or through intensive afforestation allowing the energy system to continue relying on fossil fuels (Bastin et al., 2019; Doelman et al., 2020). Two other mitigation narratives aim to minimise effects on terrestrial ecosystems, either by a rapid transition of the energy system towards renewable electricity (Jacobson et al., 2017; Sugiyama, 2012), or by rapidly reducing final demand for energy and agricultural products to reduce the pressure on the climate system (Bajželj et al., 2014; Grubler et al., 2018)..

3. Methodology

3.1. Models and methods

The Global Change Analysis Model (GCAM) was used here to analyse SDG interactions arising in decarbonisation pathways. GCAM is a dynamic-recursive, partial equilibrium model integrating human-earth system dynamics which include the behaviour and interactions of five systems: water, agriculture and land use, energy, climate and economy (Calvin et al., 2019). It has been widely used in the scientific literature for exploring technological pathways and future emissions scenarios and it was one of the four models selected to illustrate the Representative Concentration Pathways of the IPCC's 5th Assessment Report (IPCC, 2014). The GCAM version used, GCAM v-5.3 without any structural changes to the core version, can be downloaded from the public repository in Github[1] where the last changes with respect to previous version can also be checked. In order to ensure the reproducibility of the results, the policy files used for the design of the scenarios, which are not included in the core model, are provided in the Supplementary Material (SM).

Different scenarios can be set up in GCAM to simulate specific policy compatible pathways from 1990 to 2100 in 5-year time steps. Economic systems, represented by population and gross domestic product (GDP), are the exogenous drivers for system's activities. The energy system in GCAM covers primary energy resource production, energy transformation and final energy demands and includes international trade in energy commodities. It distinguishes between fossil fuel (oil, gas and coal), uranium and renewable (biomass, wind, geothermal, hydropower, rooftop solar photovoltaic and non-rooftop solar) sources. In the land use module, land is categorized and modelled based on the vegetation cover type across the 32 geopolitical regions and 235 water basins represented. Land uses can be for commercial (crops, forestry, and grazed pasture) or non-commercial (natural forest, grassland, scrubs, and other pasture) purposes. The water module balances water supply (renewable surface and groundwater, non-renewable groundwater and desalinated water) in the 235 water basins with water demand in the energy and agricultural systems.

Technology choice is determined by market competition. The market share captured by a technology increases as its costs decline, but GCAM uses an implicit probabilistic (logit) model of market competition and not a "winner take all" model of cost competition. This formulation is designed to represent decision making among competing options when only some characteristics of the options can be observed (Clarke and Edmonds, 1993). Apart from costs, stated preferences for specific technologies are taken into account through calibrated historical technology shares. More information on the methodology of economic choices can be found at https://github.com/JGCRI/gcam-doc/blob/gh-pages/choice.md. Economic land use decisions in GCAM are based on a logit model of sharing (McFadden, 1973) based on relative inherent profitability of using land for competing purposes. This logit model reflects a potential average profit over its entire distribution for each competing land use option. The share of land allocated to any given use within each water basin is based on the probability that use has the highest profit among the competing uses (Wise et al., 2015, 2014; Zhao et al., 2020). Land profits depend on yields, which in turn depend on fertilizer and irrigation inputs. More information on the allocation methodology of the land use module in GCAM can be found at https://github.com/JGCRI/gcam-doc/blob/gh-pages/land.md.

For every period, markets are cleared based on price information available at that specific time step, so the price evolution in future time periods is not taken into account in the modelling decision making process. The production outputs of the modules in GCAM are then converted not only to GHG emissions (CO_2, CH_4, and N_2O) and air pollutants (OC, BC, SO_2, NO_x, CO, NMVOC), but also to other non-CO_2 gases including HFCs which will have a significant role in the decarbonisation pathways (Ou et al., 2021).

The climate module hard linked to GCAM core modules is Hector, a simple climate model frequently used to run together with IAMs (Dorheim et al., 2020). GCAM is able to incorporate SSP narratives and uses a carbon-cycle model to replicate historical emissions, radiative forcing and surface temperatures and simulates IPCC GHG concentration trajectories, the Representative Concentration Pathways (RCPs) (Hartin et al., 2015). Hector translates emission outputs from energy, land and water modules from GCAM into terrestrial and ocean impacts. Hector's hard link with GCAM allows defining global temperature targets with a backcasting approach, which readjusts resource allocation in GCAM's modules. Hector was used in this study to set a temperature target compatible with the Paris Agreement and to explore the evolution of the ocean components of the carbon cycle to analyse the impact of the

[1] https://github.com/JGCRI/gcam-core/.

mitigation strategies on the ocean acidification process included in SDG 14 – Life Below Water.

To further increase SDG coverage, we combined GCAM outputs with *rfasst*, an R tool that replicates calculation of TM5-FASST (Van Dingenen et al., 2018) to estimate a consistent range of adverse human health and agricultural effects attributable to air pollution for a GCAM scenario. The tool can be accessed at https://github.com/JGCRI/rfasst and is documented at https://jgcri.github.io/rfasst/.

3.2. Indicators

The links between land, energy and water modules in GCAM allow the assessment of many interactive feedbacks within these sectors: Land and energy modules are connected through bioenergy and fertilizers; water, land and energy modules through irrigation and its associated energy requirements; and water and energy through the use of cooling water for energy transformation processes (Fig. 1). The water, land and energy modules are hard-linked within GCAM core and the information flows affect the results of any of the involved sectors. These capabilities make GCAM particularly useful to analyse CLEW-related SDGs. Nevertheless, the version used for this study does not include dynamic impacts of the climate systems on the other modules through, for example, water availability or impacts on crop yields.

In order to identify how GCAM can best represent SDG indicators under a nexus framework, several reports from the grey literature tracking global and regional progress towards SDG achievement have been analysed together with the official list of SDG indicators agreed as part of the 2030 Agenda for Sustainable Development (UN, 2015). These progress reports are annual reports elaborated by international think tanks, governmental and research institutions. These are: Sustainable development in the European Union (EUROSTAT, 2020), Sustainable Development Report 2020 (Sachs et al., 2020), SDG Tracker (University of Oxford & the Global Change Data Lab, 2020), The Sustainable Development Goals Report (UNDESA, 2019), Measuring Distance to SDGs Targets (OECD, 2019) and The 2019 Europe Sustainable Development Report (SDSN & IEEP, 2019).

These indicators were assessed against GCAM capabilities to identify the metrics analysed for the purpose of this study. The results are presented in Table 1, where the last column indicates whether the indicators are directly calculated from GCAM outputs or whether a model combination is used. It should be noted, nonetheless, that these metrics

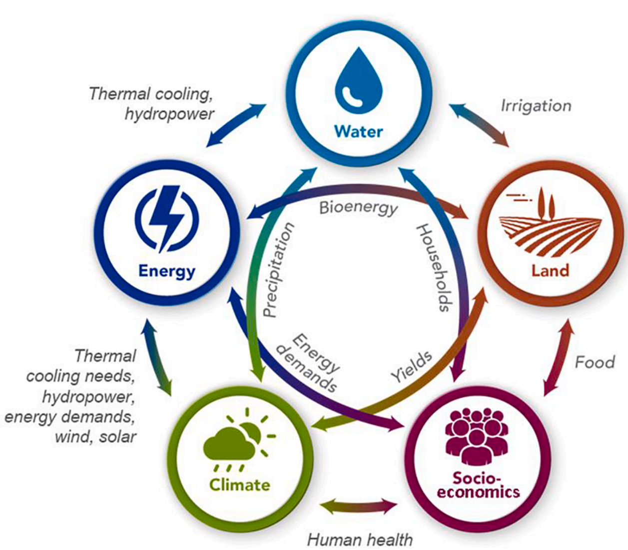

Fig. 1. Interconnections between the climate, energy, water, land and socio-economic dimensions in GCAM (Calvin et al., 2019).

Table 1
SDG indicators covered in the study and model combination used. SDG icons are the property of the United Nations.

SDG		Official Indicator		Indicator used	Model combination
2	Zero Hunger	2.c	Indicator of food price anomalies	Food price	GCAM
2	Zero Hunger	2.3	Agricultural productivity	Relative agricultural yield loss attributable to O_3 exposure	GCAM + *rfasst* (Sampedro et al., 2020b)
6	Clean Water and Sanitation	6.1	Equitable access to affordable drinking water	Water price	GCAM
6	Clean Water and Sanitation	6.4.2	Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	Groundwater withdrawals per capita	GCAM
7	Affordable and Clean Energy	7.1.1	Proportion of population with access to electricity	Household energy costs	GCAM
7	Affordable and Clean Energy	7.2	Renewable energy share in the total final energy consumption	Non-biomass renewable energy share	GCAM
11	Sustainable cities and communities	11.6.2	Annual mean levels of fine particulate matter in cities	PM 2.5 concentration	GCAM + *rfasst* (Sampedro et al., 2020a)
13	Climate Action	13	GHG emissions reduction*	Total and per capita GHG emissions	GCAM
14	Life Below Water	14.3	Minimize the impacts of ocean acidification	Ocean pH	GCAM + Hector (Hartin et al., 2015; Iyer et al., 2018)
15	Life on Land	15.1.1	Forest area as a proportion of total land area	Relative forest cover	GCAM

*Not officially part of the 2030 Agenda for Sustainable Development. SDG 13 was further developed for the Paris Agreement.

do not capture the whole dimension laid out inside each of the specific goals of the 2030 Agenda, and other factors are also likely to influence the progress or the stagnation of the SDG and its interactions with other sectors. They are therefore to be interpreted as proxies of the complex dimensions covered in each SDG.

Indicator results are aggregated according to the R5 region aggregation suggested in the SSP database (Riahi et al., 2017). ASIA includes most Asian countries except the Middle East and Japan, MAF contains countries in Africa and the Middle East, OECD incorporates OECD and EU member states and candidates, LAM stands for countries in the Latin America and Caribbean region and REF comprises countries from the Former Soviet Union which are not EU member states (Fig. 2).

Fig. 2. R5 region aggregation. ASIA includes most Asian countries except the Middle East and Japan. MAF contains countries in Africa and the Middle East. OECD incorporates OECD and EU member states and candidates. LAM stands for countries in the Latin American and Caribbean region and REF comprises countries from the Former Soviet Union which are not EU member states.

3.3. Scenarios

The scenarios explored in this study adopt background assumptions from the Shared Socioeconomic Pathway 2 (SSP2). SSP2 defines a “middle of the road” pathway in which future socioeconomic and technological trajectories do not diverge from historical ones and global population grows slowly and stabilizes after 2050. These trajectories include gradually converging GDP levels and agricultural yield gaps between developed and developing countries as well as continuously reducing costs for energy technologies. Despite some resource and energy use improvements, environmental degradation and societal challenges persist (O’Neill et al., 2014). Country climate pledges (NDC) submitted at the onset of the Paris Agreement in 2015 (high ambition interpretation, see Van de Ven et al. (2021)) are then imposed for each individual GCAM region and assumed to be met to further guide and update these assumptions.

The *Reference* scenario assumes a post 2030 emission pathway where each GCAM region reduces its emissions intensity of GDP until 2100 at the same rate as during the 2020–2030 period.

Additionally, four mitigation scenarios are designed, in order not to exceed a global mean temperature rise of 2 °C with respect to pre-industrial levels. We interpreted “well below 2 °C” defined in the Paris Agreement as “a high probability of staying bellow 2 °C” and aligned it with the latest physical research on climate sensitivity parameters

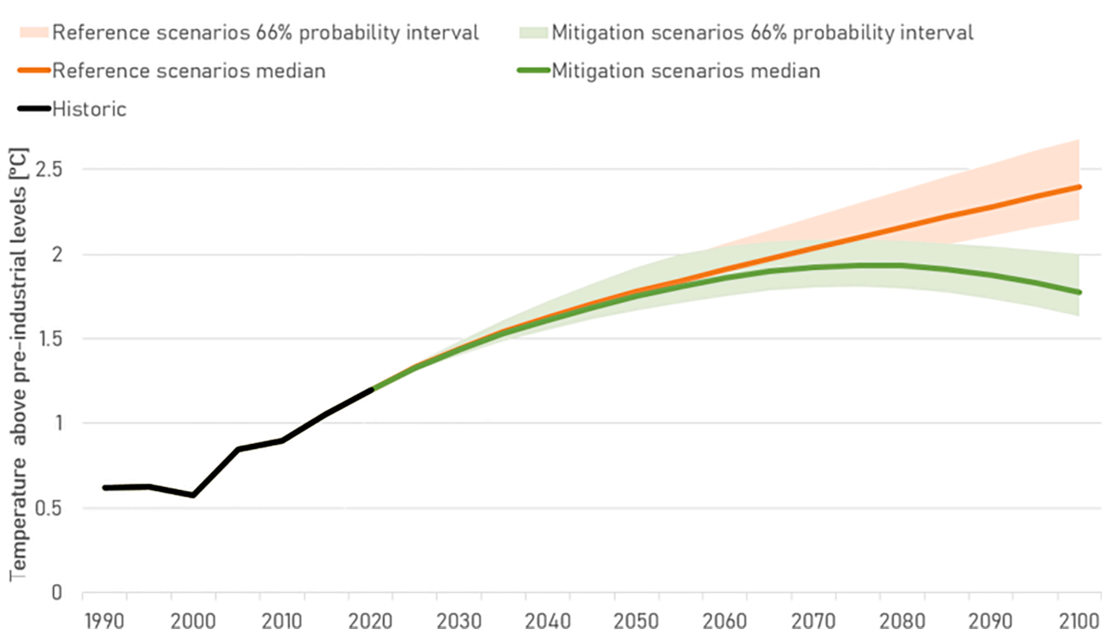

Fig. 3. Global mean temperature evolution for mitigation and reference scenarios with 66% probability range. Non-modelled data (“Historic”) taken from GISTEMP Team (2021) and Lenssen et al. (2019).

(Sherwood et al., 2020). Ensuring that the entire 66 % temperature confidence interval is below 2 °C by 2100 translates into a median temperature probability of 1.77 °C by 2100. In comparison, in the absence of Paris-compliant climate action post-2030, the continuation of ambition marked by current NDCs implies a temperature interval of 2.20–2.68 °C by the end of the century, roughly in line with Fawcett et al. (2015) and Rogelj et al. (2016) (Fig. 3).

Reference and business-as-usual scenarios have been criticized in recent literature for not reflecting current efforts to limit global warming and for not being in line with real world development (Hausfather and Peters, 2020). By including up-to-date implications of current climate commitments, a reference scenario can be built against which other scenarios can be compared and provide a more realistic picture on what additional efforts are required (Grant et al., 2020). Consequently, all the scenarios in this study assume that countries' NDC commitments for 2030 will be met. The *Reference* scenario additionally builds on the methodology developed in Fawcett et al. (2015) to develop post 2030 emission pathways based on the extrapolation of the regional emissions intensity reduction rate between 2020 and 2030. The remaining scenarios mimic four mitigation strategies that strongly differ in terms of how mitigation takes place (Table 2). The quantitative assumptions behind the qualitative model settings shown in Table 2 are detailed in section 3.1 of the Supplementary Material.

In the *Bioenergy & Capture* scenario, mitigation strategies rely heavily on the combination of CCS technology coupled to bioenergy crops. This technology is a way to obtain combustion materials while removing atmospheric CO_2 emissions. Once harvested, bioenergy crops can be processed into solid, liquid or gaseous fuels. Nevertheless, studies have also stressed that there are significant uncertainties when assessing whether fossil CO_2 avoided by the transition towards bioenergy might be offset by greenhouse gases emitted during land use conversion processes (Harper et al., 2018). Additionally, it has also been suggested that energy crops might negatively affect water consumption, biodiversity conservation (Pulighe et al., 2019) and ambient air pollution (Sampedro et al., 2020a).

In the *Forest & Fossils* scenario, reduced fossil fuel extraction cost associated with high fossil fuel social acceptance are assumed along with reliance on CCS and afforestation for mitigation. Scientific literature emphasises that there still exists a lack of analysis regarding the interactions of a large-scale deployment of CCS technologies with other elements of the 2030 Agenda (Anderson and Peters, 2016). The scientific community has also focused on the mitigation potential of large scale tree restoration especially in the context of the Paris Agreement (Bastin et al., 2019; Forster et al., 2021). However, the results of some of these studies have been contested (Veldman et al., 2019) and warnings have been made regarding top-down implementation strategies of tree plantations (Pritchard, 2021). Additionally, several studies also highlight that relying on such a strategy involves several risks in terms of land competition and, consequently, food prices (Arneth et al., 2019; Doelman et al., 2020) as well as on biodiversity loss (IPBES, 2019).

The *Electrification & Conservation* scenario mimics rapid solar and wind technology development with decreased prices of these technologies and rapid electrification of the energy system, in line with published GCAM scenario constructions (Sampedro et al., 2020a). Additionally, it also assumes that the land sector is not intensively used for mitigation purposes, not for bioenergy (Table C1.1 of the SM) nor afforestation in line with the post-2020 Global Biodiversity Framework initiative (A decisive decade, 2021).

Scenarios such as *Lesser & Greener*, where behavioural changes in wide ranges of the population are assumed, have received less attention than technology deployment in climate modelling, despite showing promising emission reduction potential (Roy et al., 2012). Samadi et al. (2017) stressed the necessity to include behavioural change patterns when designing energy-efficient scenarios due to their underestimated potential. Other studies have also stressed the potential GHG emission reductions derived from adopting sustainable habits in the diets, mobility patterns and in the housing sector (Bajželj et al., 2014; Dietz et al., 2009; van de Ven et al., 2018). Consequently, an additional policy scenario was designed with behavioural change assumptions to incorporate demand shifts related to food, transport and household demands as explored in SSP1 (van Vuuren et al., 2017).

4. Results

The aim of this study was to confront the SDG Agenda with a time horizon until 2030 and the Paris Agreement with a time horizon until 2100. While it is true that SDGs were originally defined for 2030, it is to be expected that the new set of goals defined for the period thereafter will also include these goals, as it was the case in the transition from the Millennium Development goals to the SDGs. We therefore decided not to focus on 2030 results as, first, they show very little progress with respect to the starting period in 2020 and, second, because implementing Paris-compliant policies requires shifting the focus from mid- to long-term strategies. Additionally, the decisions made during this decade to align with the SDGs will not only affect the years until 2030, but they will also define how regions progress towards the SDG Agenda in the second half of the century.

A summary of the SDG synergies and trade-offs of each scenario of this study based on Iyer et al. (2018) is shown in Fig. 4. The results presented are aggregated for the 2025–2100 period to provide an

Table 2
Scenario description and settings.

Scenario name	Description	Settings CCS supply*	Bioenergy	Solar and Wind technology costs	Land use carbon price relative to energy & industry	Social acceptance of fossil fuels**	Energy and meat demand
Reference	Post 2030 emission intensity extrapolation	Medium	No hard limit	Medium	1 %*	Medium	Medium
Bioenergy & Capture	Unconstrained bioenergy and CCS	High	No hard limit	Medium	1 %*	Medium	Medium
Forest & Fossils	Continued fossil fuel use compensated by CCS and intense afforestation	Medium	Limited	Medium	Progressive to 100 %	High	Medium
Electrification & Conservation	Wide solar and wind energy deployment without land use mitigation	Low	Limited	Low	1 %*	Medium	Medium
Lesser & Greener	SSP1 compatible behavioural changes: diets, modal shifts and building energy demands	Low	Limited	Medium	1 %*	Medium	Low

*CCS supply level is imposed through technology supply costs of CCS resources.
**Except Middle East, Pakistan, South Asia, Southeast Asia and Taiwan where LUC price is 0 of energy carbon price, since they do not include forestry in their NDCs.
***A cost adder is implemented to modify fossil fuel use and extraction cost based on social acceptance.

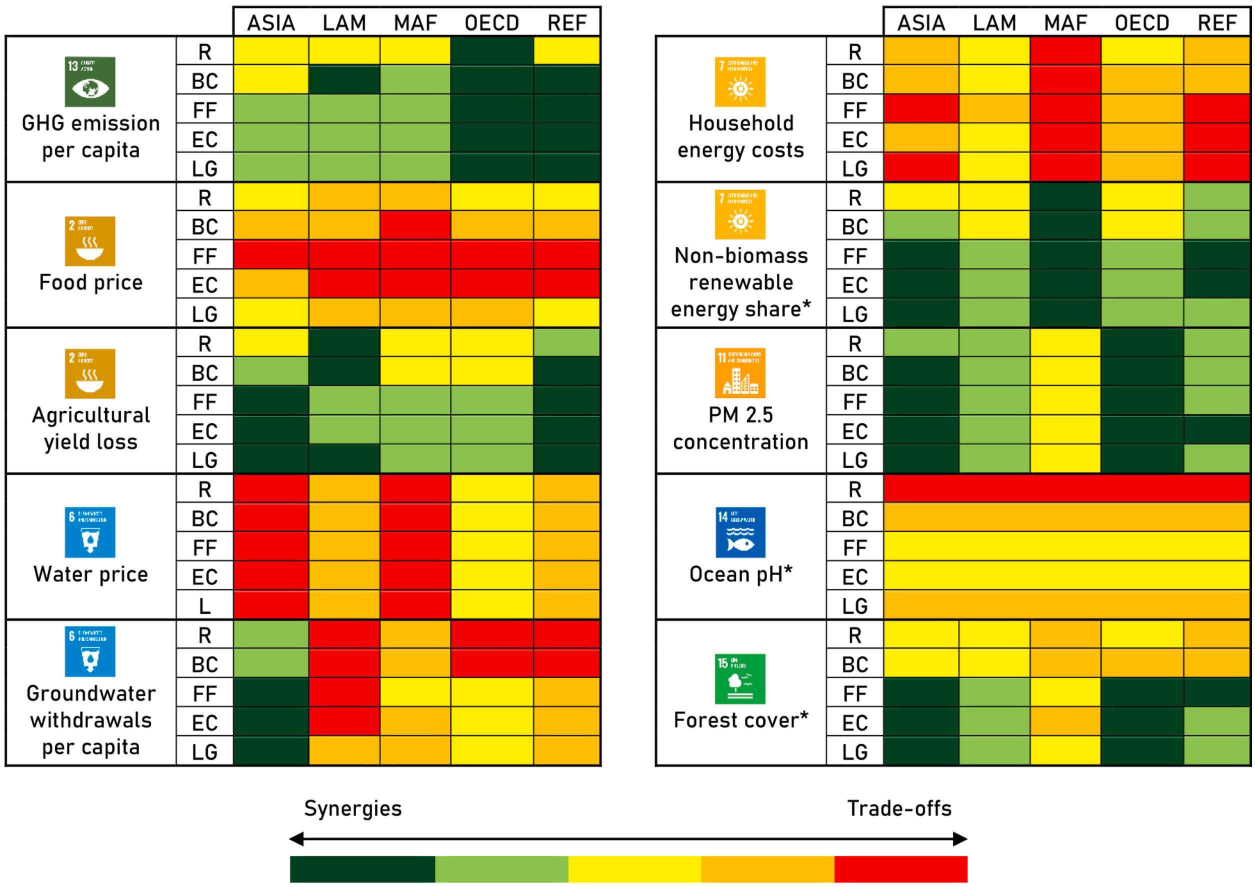

Fig. 4. Summary of SDG impacts averaged for the period 2025–2100 with respect to 2020. Acronyms of the scenario names are R for Reference, BC for Bioenergy & Capture, FF for Forest & Fossils, EC for Electrification & Conservation and LG for Lesser & Greener. Indicators include per capita GHG emissions, food prices, agricultural yield loss (attributable to exposure to ozone), water prices, groundwater withdrawals per capita, household energy costs, renewable energy shares, PM 2.5 concentrations, ocean pH and forest cover. Values are colour-coded according to the value of the ratio of the average for the period 2025–2100 and 2020, ranking the magnitude of this ratio across all regions and scenarios within the indicator. Detailed ratio figures are shown in Supplementary Figure B1. While it is true that this method makes it more difficult to compare across indicators, choosing absolute thresholds for all figures would end up hiding differences inside the indicators with all scenario-region combinations showing the same colour. Yellow colours indicate none or very little variations with respect to values in 2020. Green cells indicate ratios which reduce their magnitude with respect to 2020 and red/orange indicate increases with respect to 2020, except for renewable energy share, ocean pH and forest cover (highlighted with an *). For these indicators, red cells indicate ratios, which reduce their magnitude with respect to 2020, and green cells indicate increases with respect to 2020. Dark green (red) cells stand for lower (higher) magnitudes than light green (orange) cells, except in the mentioned indicators, where dark green (red) cells indicate higher (lower) magnitudes than light green (orange) cells. Threshold values for the colour coding were not defined in absolute terms, but rather through the value distribution within each indicator. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

overview not only of the performance at the end of the road in 2100, but also to consider the pathway followed. The data behind this figure is detailed in Table B.1 of the SM. Additionally, a more detailed disaggregation with results for 2020, 2050 and 2100 is given in Fig. 5. All the mitigation scenarios show similar global emissions levels at the end of the century, but, despite achieving the same final global goal, there could be differences among scenarios in terms of total regional GHG reductions. It is the *Bioenergy & Capture* scenario where CCS technologies acquire a central role in mitigation and bioenergy consumption is only limited by land availability, the one which could achieve the lowest regional carbon footprint among all suggested scenarios. Overall, results suggest that in order to have a global carbon footprint aligned with the Paris Agreement, OECD, REF and LAM could need to become net GHG absorbers by the end of the century.

4.1. Food prices

As a result of the settings detailed in Table 2, carbon prices in *Forest & Fossils* and *Electrification & Conservation* are higher than in the other mitigation scenarios. Higher carbon prices could raise fertilizer production prices and therefore also food prices (Fig. 5a). *Forest & Fossils* could additionally raise food prices due to increased land competition for crops as a consequence of increased afforestation. This could particularly be the case in LAM and MAF, where prices could increase by 10 by the end of the century. This land competition component could also increase food prices in a scenario with increased bioenergy production such as *Bioenergy & Capture* in line with other studies (Humpenöder et al., 2018; van Vuuren et al., 2015; von Stechow et al., 2016), but our findings suggest that this effect could be smaller than the ones induced by increased fertilizer prices and land competition due to afforestation strategies. On the other hand, *Lesser & Greener* could soften impacts on food prices and keep them at similar levels than in *Reference.*

GCAM translates policies into economy-wide carbon prices, which vary among regions but gradually converge towards the end of the century to simulate global cooperation in climate ambition as described in Kriegler et al. (2014). This approach was followed to ensure a continuous path in carbon prices and avoid sudden price jumps or reductions as a result of nationally determined NDC targets towards a global unique carbon price, which would mimic unrealistic policy representation in the medium term, particularly in regions with a low or

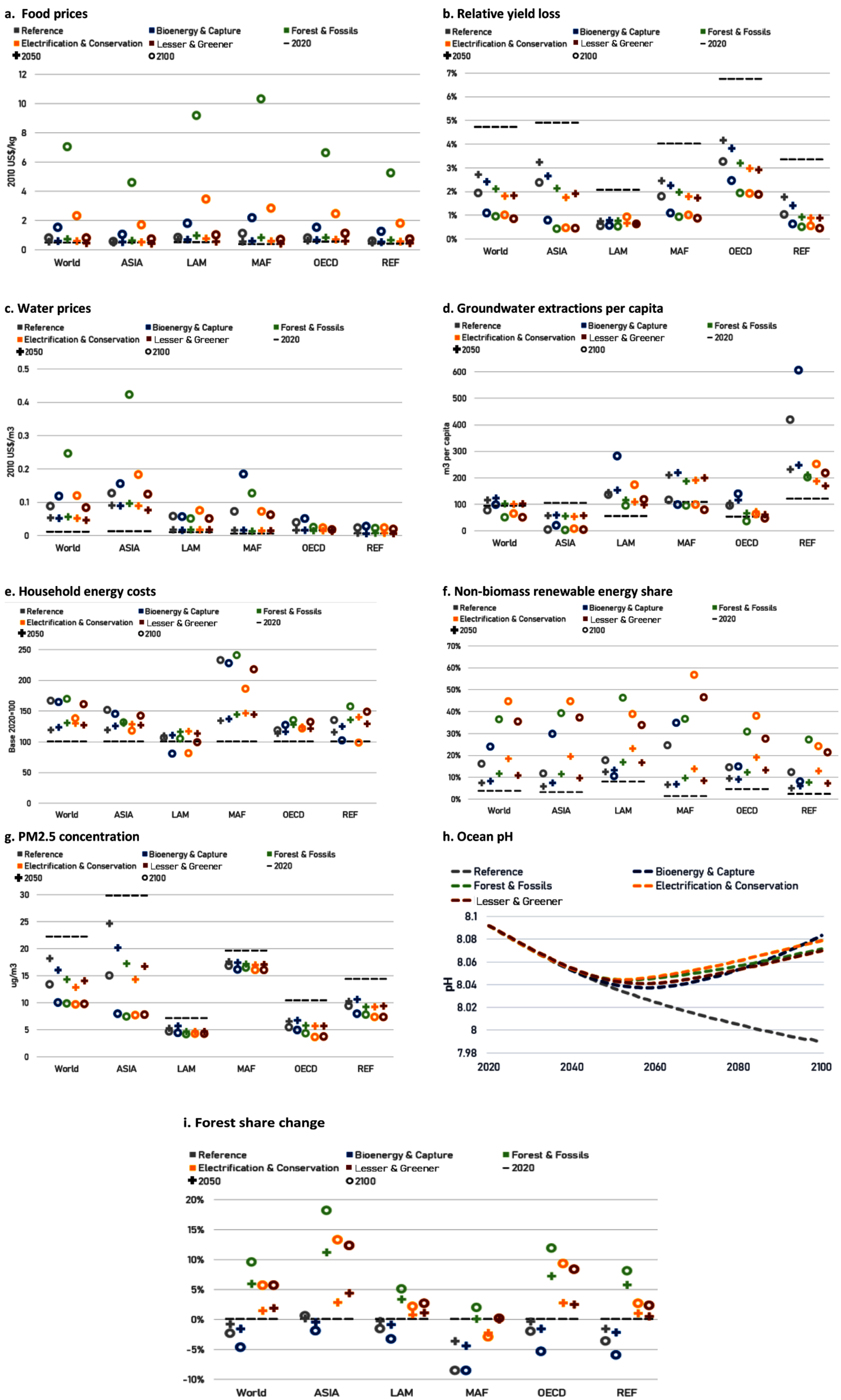

Fig. 5. Global and regional change of food prices (a), relative agricultural yield loss due to prolonged exposure to ozone (b), water prices (c), groundwater extractions per capita (d), household energy costs (e), non-biomass renewable energy share (f), population-weighted PM2.5 concentration (g), ocean pH (h) and forest share change (i) in 2050 and 2100 with respect to 2020 for Reference, Bioenergy & Capture, Forest & Fossils, Electrification & Conservation and Lesser & Greener scenarios.

high initial carbon price. In the long term, very high carbon prices in some scenarios are mainly the result of limitations to envisage future mitigation options and costs in the model. The carbon price values for the mitigation scenarios are detailed in section 3.2 of the SM.

4.2. Relative yield loss and PM2.5 concentration

Impacts on agricultural yields could also benefit from mitigation efforts, as air pollutant emission reductions would happen simultaneously to GHG emissions cutbacks. These results are in line with findings by Sampedro et al. (2020b) and Hasegawa et al. (2015). Yield losses are currently higher in OECD, and the total reduction of impacts by in the next decades would still be lower than in the rest of the regions. In our scenarios, *Bioenergy & Capture* could slightly delay this synergistic behaviour when compared with the other ones (Fig. 5b). The heavy reliance of this pathway on bioenergy could increase the emission of pollutants associated to the generation of electricity from biomass. The rise of these pollutants could increase the formation of tropospheric ozone, which is the most damaging pollutant for crop yields (Emberson et al., 2018) and offsets any potential carbon or other fertilization effects derived from anthropogenic GHG emissions (Shindell, 2016). This could prolong the exposure of agricultural land to higher ozone concentration levels and delay the crop damage drop. The same reason would apply for the delayed reduction of PM2.5 concentration levels in this scenario (Fig. 5g). Concerning this impact, the MAF region would the one with the greatest gains.

4.3. Water prices

Increased afforestation efforts in *Forest & Fossils* could take place in regions with higher carbon price and high forest yield such as OECD. To accommodate for this afforested land, food crops could be shifted to regions such as the Indus basin (ASIA) with low forest yields. This would substantially increase the pressure on water resources and, consequently, its price (Fig. 5c). In contrast, those regions attractive for afforestation could benefit from a decrease in water prices due to water stress reduction. *Lesser & Greener* could also smooth trade-offs for this indicator, keeping water prices at levels comparable to their values in 2020. The latter cannot be inferred from Fig. 4 due to the methodology chosen for the colour coding, but it can be noticed in Table B.1 of the SM.

4.4. Groundwater extractions

Bioenergy & Capture could require additional water extractions (Fig. 5d) due to the increased demand of bioenergy crops. Our results also suggest that it would be mainly the basins in in LAM and REF the ones bearing the burden of the additional groundwater extractions used for the transformation of biomass to electricity with CCS. *Lesser & Greener* and *Forest & Fossils,* on the other hand, suggest the opposite behaviour and they could contribute to reducing groundwater extractions. These confirms the outcomes highlighted in other studies focused on these impacts (Bonsch et al., 2016; Humpenöder et al., 2018; Popp et al., 2011).

4.5. Household energy costs

Projections for the indicator on household energy costs suggest that in most regions, *Electrification & Conservation* could increase costs in the mid-term (Fig. 5e). However, in the long term, results suggest that reduced electricity prices and higher electrification rates in this scenario could compensate for the growth in demand and achieve the lowest household energy costs increase among the mitigation scenarios.

4.6. Renewable energy

As it could be expected, *Electrification & Conservation* would imply a high global non-biomass renewable energy share (Fig. 5f). In contrast, the mitigation alternative suggested in *Bioenergy & Capture* could moderately delay the use of other renewable energy sources particularly in LAM and REF, as mitigation through BECCS could discourage the use of other renewable energy sources. Consequently, *Forest & Fossils* and *Lesser & Greener* could outperform *Bioenergy & Capture* on this indicator at global level.

4.7. Ocean pH

Mitigation pathways also suggest synergistic effects with the reversal of the ocean acidification process (Fig. 5h) in line with Iyer et al. (2018). All the suggested mitigation scenarios could stop the process at very similar rates and leave pH values in 2100 at similar levels to the 2025–2030 period, but *Reference* suggests that the extrapolation of current climate ambitions after 2030 would not be able to halt this trend.

4.8. Forest share

Unsurprisingly, *Forest & Fossils* suggests an increase in the total forest cover when compared with the other mitigation scenarios (Fig. 5i). ASIA and OECD show the highest increase in forest cover with respect to the *Reference* scenario in 2100. The combination of high carbon prices and high forest yields in USA, China, EU and Southeast Asia could attract afforestation efforts to these regions and foster terrestrial carbon accumulation while moving crops to basins in other regions with low forest yields. On the other end, *Bioenergy & Capture* could increase land competition and limit forest cover expansions.

5. Discussion

As already noted in recent scientific publications, policies in place are not sufficient to comply with the Paris Agreement even if current ambition in continued throughout the century (Roelfsema et al., 2020; Sognnaes et al., 2021). An increase in effort is required to keep global mean temperatures well below 2 °C and the pathways followed will have an impact on other (at least) equally important aspects according to the sustainable development agenda. Along this path, it is unlikely that the entire world uniformly adopts a unique mitigation strategy that reproduces the trends described in this study, as countries will follow different approaches that will not rely entirely on one of the suggested pathways. The purpose of this specific scenario design is therefore not to predict probable mitigation trajectories, but rather to highlight possible consequences if any of the pathways included in this study gains momentum in the coming decades and is able to influence global trends affecting SDG interaction evolution.

The designed mitigation scenarios explore alternatives where emission reductions are coming from both the demand and supply side. The former incorporates behavioural changes in the population and the latter include strategies relying on land use, on renewable energy technologies and on carbon capture techniques for mitigation purposes. These scenarios were considered to assess the interactions of the following indicators: agricultural yield loss, food price, water price, groundwater withdrawals, household energy costs, non-biomass renewable energy share, PM 2.5 concentrations, GHG emissions, ocean pH and forest cover. Based on our analysis, several conclusions can be drawn.

5.1. Key SDG synergies and trade-offs

Increased efforts to decarbonise economies and align them with the temperature goals in the Paris Agreement could have implications on several aspects of the SDG Agenda depending on the policies implemented. The nature of these implications are consistent throughout all the timescales analysed, but they become more evident the further the time horizon goes. The pathways suggested here which rely on technological and nature-based solutions show trade-offs with food and water prices, groundwater extraction rates, exposure to PM2.5 particles, yield impacts or ocean acidification. On the other hand, the scenario with more sustainable behavioural choices could reduce negative impacts on food and water prices while quickly improving ambient air pollution and agricultural yield. Scenarios explored also suggest indicator synergies on which polices can rely to simultaneously progress towards multiple SDGs. Progress on SDG 13 – Climate Action can also reduce agricultural yield impacts associated with exposure to ozone, improve ambient air quality and reverse ocean acidification with different speed rates depending on the policy implemented. Additionally, they could also boost the renewable energy share in SDG 7 – Affordable and Clean Energy or the forest cover in SDG 15 – Life on Land. A summary of the key positive and negative interactions is given in Fig. 6.

Following specific mitigation trajectories will have both positive and negative socio-environmental interactions of different nature. If mitigation is shifted mainly to the supply side, there is an increased risk that it would impact on water resources, delay emission reductions and cause water and food prices to escalate limiting access by more vulnerable populations. Additionally, the predominant economic system has historically undervalued environment and ecosystem services, so little incentive has been given to technological innovations aimed at stopping environmental degradation. This makes waiting for a future technological breakthrough a risky mitigation strategy (Heuberger et al., 2018; Spaiser et al., 2017). On the other hand, it is more likely that unintended interactions are reduced if policies incorporate a focus on the demand side and encourage societal behavioural changes in diet, transport and consumption patterns.

5.2. Limitations and further research

This study covers the interconnections of a wide range of SDG-related dynamics in contexts of mitigation alternatives. This attempt included soft linking GCAM outputs with simple climate and air quality models but implied that some climate change feedback effects between the analysed variables were not considered.

The changes in agricultural yield only include the effect of exposure to tropospheric ozone. While literature stresses that it is the most damaging pollutant for crop yields, effects of other GHGs including carbon fertilization effect would also be required for more accurate projections. Other relevant effects on agricultural yields that were not considered in this study are those caused by precipitation and temperature changes. Yields effects were calculated ex post and do not include feedbacks with GCAM, so they were not taken into account for the food price indicator results. We also did not consider feedback effects of climate change on socioeconomic parameters such as population or economic shifts or on macroeconomic variables such as employment. Accounting for the latter would isolate climate change mitigation effects and would further improve the results.

Additionally, GCAM's least-cost optimization algorithm shifts and replaces processes across the regions seeking for the cheapest way to achieve the required global objectives. Trade markets in GCAM can be global or regional depending on the commodity. Major energy commodities (coal, gas, oil, bioenergy, etc) are traded in a world market while most agricultural and livestock commodities are traded in regional market with consumers' perceptions on traded goods taken under consideration for computing products' demand. GCAM also assumes that secondary energy products are not traded within regions. Consequently, indicators used to measure SDG evolutions reflect transformations happening in a certain territory, but they may be driven by dynamic shifts in other regions.

Food, water and energy price projections could be affected by additional factors aside from the ones arising from mitigation dynamics covered in GCAM. The least cost optimization approach of the model operates with recursive dynamics and adaptative expectation about prices, so they do not take into account all dynamics that could affect food, water and energy prices in the future. In particular, food prices increases in the *Electrification & Conservation* scenario are heavily driven by the fact that GCAM does not consider any renewable energy source other than bioenergy for the production of fertilizers. Since reliance on bioenergy is constrained in this scenario, high carbon prices imply higher costs associated to fertiliser production and, consequently, higher food prices. It is, nonetheless, possible that in the timespan covered during this study other renewable alternatives are used for the production of fertilizers (e.g. hydrogen) which would then smoothen the food price increase.

Finally, it is also worth noting that only some aspects of SDGs dimensions are covered in this study, as analyses are limited by modelling capabilities. IAMs still require further development when representing social aspects of the agenda such as education, equality or gender and other cross-cutting issues such as sustainable consumption and production behaviours, biodiversity or ecosystem services (Allen et al., 2016, 2017).

A recently published co-authored report by the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Pörtner et al., 2021) alerted on the linkages between the climate and the biodiversity crisis and urged policymakers to tackle both

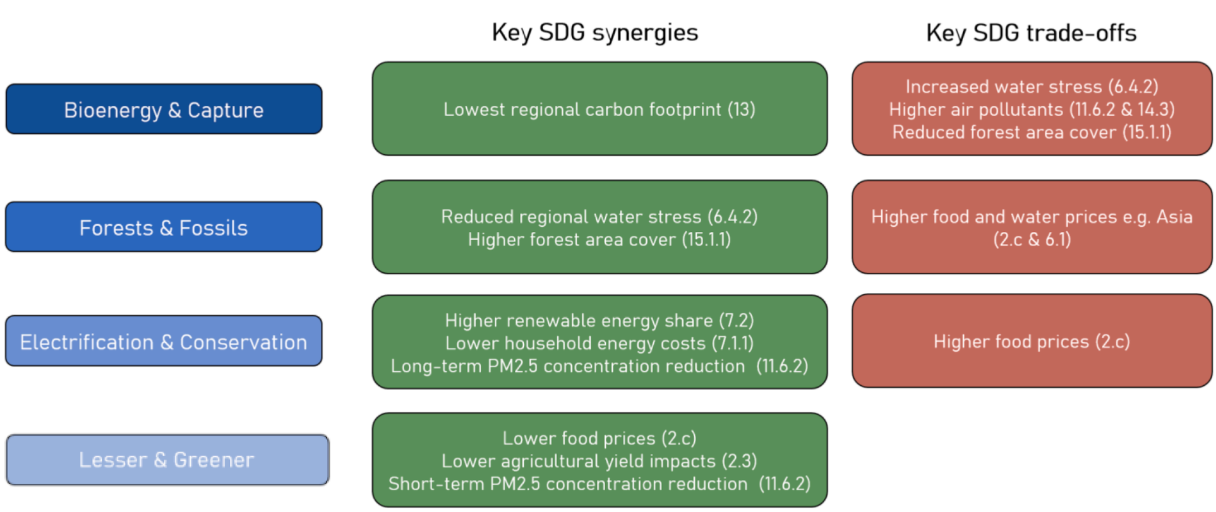

Fig. 6. Key SDG interactions in the four modelled mitigation scenarios. Values between brackets refer to SDGs and SDG targets.

simultaneously to avoid potential trade-offs. There is therefore also a need to expand SDG interactions studies such as this one to further explore the biodiversity-related effects of mitigation strategies.

6. Conclusions

In this paper, we explore the implications of several mitigation alternatives on specific SDGs in the 2030 Agenda. We analysed the potential interactions when aligning with the Paris Agreement to limit temperature rise in 2100 and trying to keep it "well below 2 °C" compared to pre-industrial levels. Based on a backcasting approach using the integrated assessment model GCAM, we designed scenarios to reduce GHG emissions and compared the results with a scenario that extrapolates the mitigation efforts in current climate pledges from 2030 to 2100.

Unlike most of the modelling assessments so far, we covered the whole world for completeness while also focusing on the main regions to track the geographically diversified impact of mitigation strategies on different SDGs, while also accounting for possible spill-over effects among regions. Furthermore, rather than assuming combinations of technological or behavioural solutions, we designed four mitigation scenarios relying on predetermined decarbonisation strategies. The SDG interconnections increasingly explored from multiple viewpoints call for strategies which go beyond the focus on GHG emission reduction and adopt wider visions to envisage how to reinforce synergies and minimize trade-offs of relevant SDG dimensions.

Our results suggest that channelling mitigation through behavioural changes, apart from having enough potential to keep temperature levels "well below 2 °C", has both environmental and social advantages. This does not imply shifting the burden and the responsibility to the society, it is rather a call to for policies to be oriented towards incentivising the transition towards more sustainable habits. The world has witnessed a recent example of the potential of behavioural changes during the strict covid-19 lockdowns which resulted in the largest drop in emissions (Le Quéré et al., 2020). Even though the other implications of that scenario are not desirable, there are certain habits adopted during that period such as teleworking or the replacement of face-to-face meeting by video calls which could outlive the pandemic period. Along that same line, the IEA has also presented a plan to cut oil use relying specific policies which include a change of habits in light of geopolitical instabilities. (IEA, 2022). These measures adopted in crisis contexts provide examples of the mitigation potential of demand-side changes and could inspire policies to address the climate crisis we are facing.

Roads to a Paris-compatible world do not come at a (sustainable) zero cost. Possible adverse consequences need to be anticipated so that policies can be carefully designed to address them and exploit the reinforcement of potential synergies at the same time. Adopting a holistic vision and setting a framework which focuses on multiple interdependent and interacting goals such as the 2030 Agenda may have the risk that failing to achieve one objective will jeopardize others with reinforcing relation. However, it is the only possible strategy which allows individual goals to be pursued whilst keeping track on the overarching goal.

CRediT authorship contribution statement

Jorge Moreno: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Visualization. **Dirk-Jan Van de Ven:** Conceptualization, Methodology, Validation, Writing – review & editing, Visualization. **Jon Sampedro:** Validation, Writing – review & editing, Visualization. **Ajay Gambhir:** Validation, Writing – review & editing, Visualization. **Jem Woods:** Writing – review & editing, Supervision. **Mikel Gonzalez-Eguino:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2022.102624.

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