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Integrated scenarios to support analysis of the food–energy–water nexus

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The literature emphasizes the important relationships between the consumption and production of food, energy and water, and environmental challenges such as climate change and loss of biodiversity. New tools are needed to analyse the future dynamics of this nexus. Here, we introduce a set of model-based scenarios and associated Sankey diagrams that enable analysis of the relevant relationships and dynamics, as well as the options to formulate response strategies. The scenarios show that if no new policies are adopted, food production and energy generation could further increase by around 60%, and water consumption by around 20% over the period 2015–2050, leading to further degradation of resources and increasing environmental pressure. Response strategies in terms of climate policies, higher agricultural yields, dietary change and reduction of food waste are analysed to reveal how they may contribute to reversing these trends, and possibly even lead to a reduction of land use in the future.

The use of key natural resources, such as food, energy and water, to support human development has increased considerably during the past few decades. For instance, the consumption of cereals and energy has grown around four- and six- to sevenfold, respectively, since 1960[1,2], reflecting the threefold increase in global population and an increase in per-capita consumption levels. The resulting production levels of these resources have spurred economic development, but have also led to sustainability and environmental challenges, such as resource depletion, climate change and biodiversity loss[3]. At the same time, there are billions of people who have only limited access to resources such as food and energy. Academic studies have started to emphasise the important interdependencies among the production systems of these key resources and global environmental issues, referring to this as the food–energy–water nexus[4,5]. So far, the lion's share of the nexus literature has focused on local linkages, or rather qualitative descriptions of existing linkages[6–10]. Relatively few integrated studies exist that analyse the linkages across time and geographic scales[11], with some notable exceptions[12–14]. In contrast, a wide set of model-based emissions scenarios have provided a basis for decision-making on climate change. Here, we respond to the urgent need for new analytical frameworks, scenarios and visualization tools that provide a basis for nexus analysis[15,16], exploring how the use of natural resources can stay within 'planetary boundaries'[17], while at the same time ensuring decent living conditions for all (the Sustainable Development Goals adopted in 2015 are aiming for such a balance by 2030[18,19]). Shifting focus from exploring how things may go wrong if current trends continue to analysing possible response strategies is an important component of this. It should also be noted that different tools are needed to fully analyse the different aspects involved in assessing the feasibility of the options discussed. Here, we focus on the biophysical and technical aspects, while in follow-up steps, it will be useful to look further in the socio-political and economic aspects.

The energy and agricultural systems form the backbone of this nexus. For instance, the expansion of agricultural land is a key driver of biodiversity loss[3], and agriculture also takes the lion's share of total freshwater withdrawal and accounts for a significant share of greenhouse gas emissions. Foley et al.[20] indicate that a sustainable agriculture system should feed the world population while contributing to mitigating climate change and stabilizing global land use. They propose several response strategies that could contribute to achieving this, including: (1) shifting towards less meat-intensive diets; (2) increasing agriculture yields and feed efficiency; (3) reducing food waste; and (4) preventing climate change by reducing greenhouse gas emissions of all sources. This paper takes their strategies as a starting point for a set of future scenarios that provide a unique integrated overview of possible development paths to analysing the dynamics of the nexus across geographic scales, and to explore the effectiveness of the four response strategies. The scenarios were developed using IMAGE 3.0 (ref. [21]) combined with projections for per-capita food demand using the food demand model (FDM[22] (see Methods). IMAGE is an integrated assessment model with a strong and relatively detailed representation of the relevant biophysical and technology dynamics of both the human and Earth system, making it relevant to focus on the nexus connections at different geographical scales (global regions and at the grid level). IMAGE includes many key connections between the various systems, including the climate impacts on natural systems (here, we did not include the uncertain climate change impacts on agriculture systems, in line with the protocol for the shared socio-economic pathway (SSP) implementation). Other integrated assessment models are more rooted in economic modelling traditions, and as a result have a stronger representation of the relevant economic linkages (such as long-term growth models and other macro-economic models) (https://www.iamcdocumentation.eu/index.php/IAMC_wiki). Consistent with the strengths and weaknesses of IMAGE, the analysis presented here focuses on scenarios that describe technically and physically possible options. The analysis does not attempt to represent policy or other societal strategies for achieving this technical potential, nor does it try to quantify the economic implications. Although the results presented here are at the global scale, calculations were also

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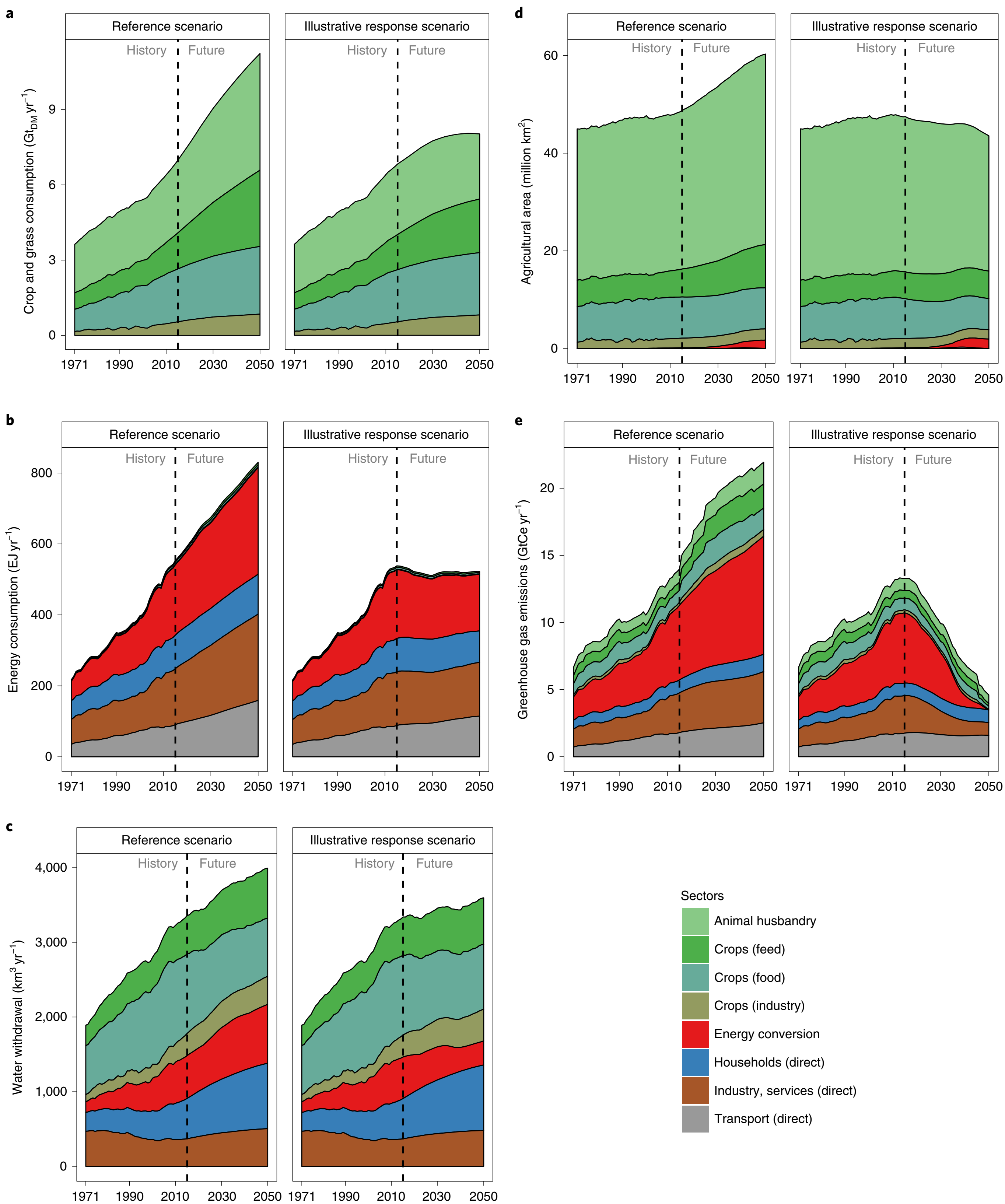

Fig. 1 | Resource consumption and associated impacts for the SSP2 reference and illustrative response scenarios over time. a–c, Consumption of agricultural products (**a**), energy (**b**) and water (**c**). **d**,**e**, Associated impacts on land use (**d**) and greenhouse gas emissions (**e**). In all panels, the reference scenario is shown on the left and the illustrative response scenario is shown on the right. The vertical dashed lines represent the present date (at the time of publication). The legend applies to all panels. GtCe, equivalent carbon emissions (based on 100-yr GWPs); Gt_{DM}, gigatonnes of dry matter. FDM[23,40] and IMAGE[22] calculations were used to create this figure.

done for the underlying regions, and at the detailed grid level (see Supplementary Information). The reference scenario is the IMAGE implementation of the SSP2 (middle-of-the-road) scenario[23], in which basic drivers such as population, income and technology are assumed to follow 'middle-of-the-road' trends (see Methods). The projections made by the scenarios are presented in Sankey diagrams, which emphasize the key connections between the various systems, indicate key leverage points and serve as a method to advance nexus analysis. Sankey diagrams are flow diagrams in which the widths of the arrows are proportional to the flow quantity[24,25]. Connected Sankey diagrams for different nexus resources were used earlier in local studies (for example, refs. [10,26]), or to illustrate inefficiencies in the food system (for example, ref. [27]). Here, they are used to analyse key leverage points where the system can be made more sustainable, and show the connections between the various nexus elements. In each figure, a comparison is made between the reference scenario and response scenarios, which are described in more detail below.

Further growth of energy, food and water consumption

There are strong correlations between income levels and the consumption of food and energy and, to some degree, water[22] (see also Methods). For food, the consumption of animal products, sugar and oil products in particular continues to grow as income levels increase. On average, above a per-capita income of around US$10,000 yr^{-1}, food intake starts to level off (see Methods). Similar relationships exist for several energy and water services, but with different rates of growth and saturation levels. Based on these relationships, the reference scenario shows that, if no new policies are adopted, global consumption of food, energy and water is expected to increase significantly (Fig. 1a–c (note that the integrated response scenario is introduced later)). All figures show aggregated units (for example, tonnes of dry matter), but underlying calculations are made in terms of the services provided (that is, the contribution to calories and protein for food; see Methods). For food consumption, the projected 60% rise in the period 2015–2050 (in tonnes of dry matter) is dominated by an increased consumption of meat (Fig. 1a; increase in both animal husbandry and crops for feed), as was also seen in sectoral scenario studies[22] . Most of the increase in consumption is projected to occur in low-income regions as they catch up with the already much higher levels of food consumption in countries that are members of the Organisation for Economic Cooperation and Development. As for energy consumption, the reference scenario projections show a similar increase (up to 60% by 2050; Fig. 1b), with the highest increases in the energy conversion and transport sectors, again consistent with a range of other baseline scenarios[23], Finally, global water consumption is projected to increase more modestly (by 17% in 2050 (Fig. 1c)), mostly driven by the consumption of individual consumers and industries. Some scenarios in the literature show a more rapid increase, but these may underestimate the effects of efficiency improvement in energy systems (leading to less water consumption)[28].

The increase in resource consumption is projected to lead to environmental impacts via additional land use and greenhouse gas emissions. Most of the increase in agricultural production is projected to be covered by yield increases (for instance, by a 25% increase for temperate cereals and rice in the 2015–2050 period). This is consistent with other baseline projections (the IMAGE SSP2 scenario roughly follows the Food and Agriculture Organization (FAO) projections). Despite the important role of yield increase, the reference scenario still shows an increase in agricultural area of more than 10% between 2010 and 2050, again consistent with historical trends[29] (Fig. 1d). The expected increase in greenhouse gas emissions is mostly driven by a further rise in fossil fuel combustion and increasing non-CO_2 emissions from agriculture (Fig. 1e).

Sankey diagrams to identify inefficiencies

The Sankey diagrams (Figs. 2 and 3) offer a visualization of the complex conversion pathways and leverage opportunities in the system for improving resource use. They connect the resources (left) with the end-use categories (right). Sankey diagrams have frequently been used to represent existing situations (for example, ref. [27]) and, in some cases at the local scale, also scenarios (for example, ref. [10]), but here we present scenario-based global Sankey diagrams for 2050 for all nexus resources and relevant connections. For food, the diagrams show how biomass taken from the land (expressed as dry matter mass) is converted into food products or lost as food waste. Similarly, they show for energy how the primary energy carriers are converted into final-use carriers (including electricity), and finally into end-use services. Arrows exiting the diagrams on the right represent useful flows, and arrows exiting downward indicate the proportions of resources that are not converted into end products (including waste categories, but also some re-use of resources (see below)). The diagrams provide insight into the efficiency of the system, while the waste flows highlight possible leverage points. In Fig. 3, we connect the individual flows into a fully integrated Sankey diagram.

The food diagram (Fig. 2a, reference scenario) shows that most of the throughput is related to animal husbandry as feed. A relatively small amount of the dry matter is used for final consumption. A much larger amount leaves the system, including the food crop residues, animal feed and post-harvest food waste. Clearly, these flows are not mere losses. Residues are partly used to prevent soil degradation or to recycle nutrients[30]. The diagram clearly shows opportunities that can be used to leverage the efficiency of overall system performance, such as a reduction in the large flows used for animal products. While the energy diagram (Fig. 2b) suggests that considerable losses occur during electricity generation, it should be noted that often electricity can be used much more efficiently than other energy forms at the point of end use. At the same time, large losses at the end-use side are also shown[1,31] (although it should be noted that precise definitions of efficiency are somewhat difficult). Figure 2b also shows the (slow) transition towards renewable energy in the SSP2 baseline. Without climate policy, this transition is still limited as result of the limitations of renewable energy penetrations (and associated cost increases) and the size of the power sector. This is consistent with other baseline scenarios[32]. The water diagram (Fig. 2c) looks more complicated, given the intertwinement of natural and anthropogenic flows. Two typical examples are the use of precipitation for agricultural crops, and the recycling of stream discharge as irrigation water. The main end-use functions for water are agriculture, residential water use, the energy system (cooling) and industry (the graph does not show ground water use due to a lack of data). Above all, the diagram emphasises the relatively large size of natural flows compared with anthropogenic use from a global perspective. However, it should be noted that local scarcity can be very important. Finally, Fig. 2d shows how food and energy flows are connected to different forms of greenhouse gas emissions.

The Sankey diagrams can also identify key connections between the resource flows, Measures for change must therefore be evaluated with these connections in mind, as they could lead to synergies and trade-offs. For instance, the structures of the energy and food systems play a key role in water use. Also, the bio-energy flow in the energy system has a bearing on land use in the food system.

Options for change

Foley et al.[20] introduced four key options for change without further analysis of their impacts or the complex inter-relationships with other nexus issues. Here, we show an analysis of the possible consequences in terms of nexus relationships. The aim of the calculations is to take a further step in the analysis of the options by illustrating the strategies' potential impacts in terms of biophysical and technical consequences (Table 1), given the methodological strengths and weaknesses of the

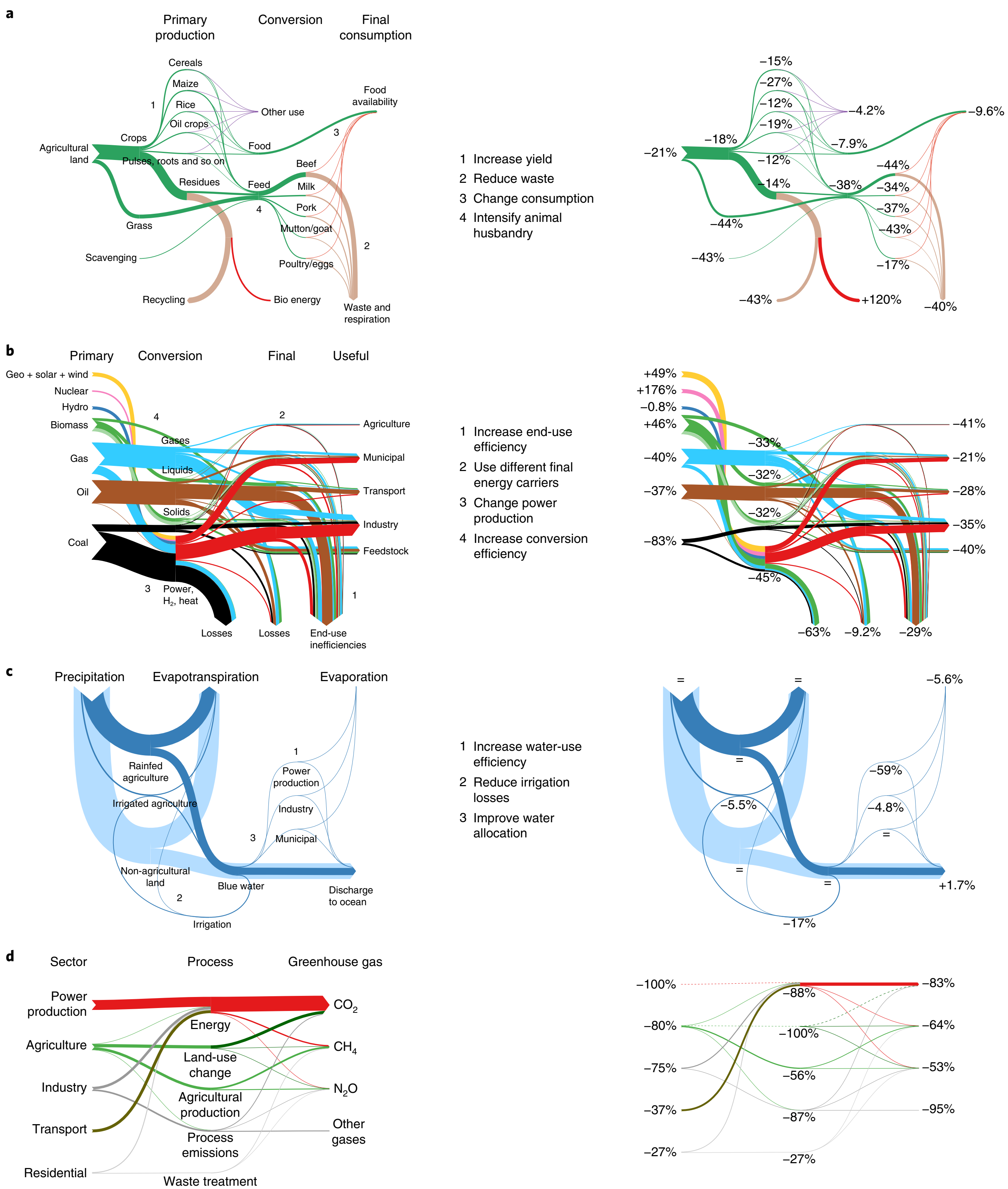

Fig. 2 | Sankey diagrams showing 2050 projections of the SSP2 baseline and response scenarios. a–d, Sankey diagrams for the reference scenario (left) and illustrative response scenario (right), representing flows in agricultural products and land use (**a**; kg dry matter), energy (**b**; J), water (**c**; km^3) and the resulting greenhouse gas emissions (**d**; CO_2e). Leverage opportunities are listed at the centre of each set of diagrams. Line widths are proportional to the magnitude of the corresponding flow, and line colours match the legend in Fig. 1. In **c**, flows that pass through anthropogenic uses, such as agriculture and cooling, are plotted separately (using a darker shade) on top of the natural flows. In **d**, some emission sources on net remove greenhouse gas from the atmosphere thus become negative, indicated by dashed lines. In the main text, we discuss the leverage points for food in detail. Those for energy form part of our climate policy. In this study, we did not look at the leverage points for water in our scenarios. FDM[23,40] and IMAGE[22] calculations were used to create this figure.

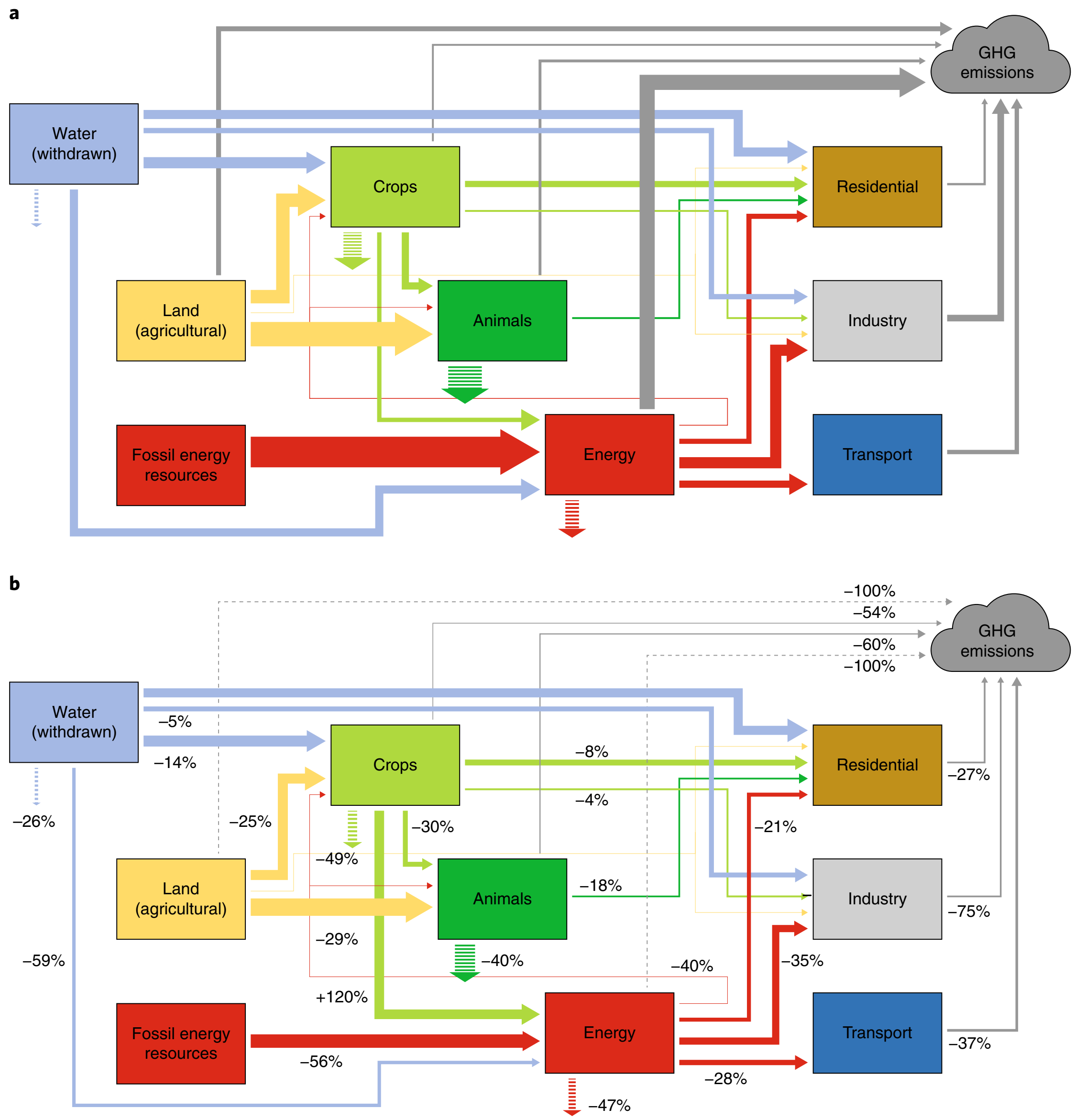

Fig. 3 | Linkages between the different agriculture, energy and water systems. a,b, Global projections of the reference scenario (**a**) and illustrative response scenario (**b**) for 2050. The arrow widths are proportional to the total volume of each flow type (water (blue), land (yellow), biomass (green) and energy (red)) under the reference scenario. Associated greenhouse gas emissions are shown in grey. Waste flows are indicated by short dashed lines pointing down. The percentages in **b** reflect the differences compared with the reference scenario. GHG, greenhouse gas. Flows that lead to net removal of CO_2 from the atmosphere ('negative emissions') as simply indicated as a 100% reduction and shown by dashed lines.

methods used (see Supplementary Information), but also the normative assumptions on which they are based. Clearly, the degree to which these strategies can be implemented depends on social, institutional and political factors. We only look at direct impacts at the global level, as the calculations do not account for all economic feedbacks. For example, a lower demand for agricultural land is likely to result in decreasing prices for agricultural products, and could thus lead to a larger demand for such products. While such feedback would increase food security, it leads to lower effectiveness in terms of preventing environmental damage. There is also a risk that lower food prices would slow down agricultural investments, thus undermining the yield assumptions of the scenarios. Similar feedback processes can also be relevant for other options. It will be important to analyse the scenarios using other tools, including economic models.

Shift towards less meat-intensive diets. Moving towards less meat-intensive diets can also be an important way to decrease agricultural land use and thus reduce emissions from land-use and land-cover changes[20,33–38]. This is because the inefficiency in the food system is associated with animal products (Fig. 2a). While meat consumption per capita has strongly increased over time, there is also evidence that adherence to vegetarian diets has grown slightly in developed countries[39]. However, even a moderate reduction in meat consumption to amounts consistent with recommended 'healthy' levels, such as the Willett diet (see Table 1), would significantly reduce meat production, thereby leading to a 30% decrease in feed production relative to the reference scenario (see Fig. 3). Greenhouse gas emissions would also decrease (Fig. 4), due to reduced emissions caused by land-use changes, the regrowth of forest on abandoned agricultural land, and the reduction of non-CO_2 emissions from animal husbandry. Similar results might be obtained by replacing conventional animal-based meat with cultured meat produced using stem cell technology[40].

Table 1 | Options for change

	Baseline setting	Individual options	Assumptions made in the integrated response scenario
Shift towards less meat-intensive diets	Regions follow normal diet patterns as prescribed by the SSP2 implementation of the FDM model (see Supplementary Information).	Meat consumption is restricted to a 'healthy' level in all regions in 2050 (Willett diet), assuming a weekly per-capita consumption of 70 g beef, 70 g pork and 350 g chicken and eggs[36,37].	By 2050, 44% of the people in each region follow the Willett diet and 56% still follow their conventional diet.
Increase agriculture yields and feed efficiency	Yields and feed efficiency follow the SSP2 baseline scenario (for example, a 24% increase in cereal crop yields up to 2050, consistent with the FAO scenario).	Yields are improved by 15% compared with the reference scenario, based on the IAASTD[42], in combination with a 50% convergence in all regions to the highest feed efficiency (Western Europe).	Yields are improved by 7% compared with the reference scenario, and feed efficiency improvement is halved.
Reduce food waste	Food waste loss follows a log-linear relationship with income, implying a slow increase in consumer losses.	Storage and distribution of food waste fractions are reduced by 86% in 2050. For household food waste fractions, 98% of avoidable waste is handled correctly in 2050.	Storage and distribution of food waste fractions are reduced by 45% in 2050. For household food waste fractions, 49% of avoidable waste is handled correctly in 2050.
Climate policy	No climate policy is included.	Climate policy is calibrated to stay within 2 °C, implemented through a uniform global greenhouse gas emissions price across all emissions sources, which rises over time.	Climate policy is calibrated to stay within 2 °C, implemented through a uniform global greenhouse gas emissions price across all emissions sources, which rises over time.

Increase agriculture yields and feed efficiency. Many studies have indicated that it is possible to increase yields further, especially by reducing the yield gap in developing countries[20,41–43] or by using new technologies, including data-driven precision agriculture, through which damage to environmental systems can be prevented through measures such as better nutrient and water management[43]. In the analysis, we included a 15% yield improvement compared with the reference scenario, in accordance with the attainable level according to the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) expert assessment[42], in combination with an intensification of the animal production systems[23]. The results show that improved yields and feed efficiencies can significantly reduce global land use for agriculture and livestock farming, and therefore also greenhouse gas emissions (Fig. 4).

Reduce food waste. It is estimated that roughly one-third of global food production is wasted[44]. While the highest levels of food waste per capita at the retail and consumption stages occur in high-income countries, there are significant losses in the post-harvest, processing and transportation stages for all countries. This implies that there is scope for improvement globally [44]. Taking into account the actual waste and avoidable waste fractions per food category[37], the calculations performed here show that measures to reduce avoidable food waste by half (15% points) could lead to an 8% decrease in total food production, a 6% decrease in land use, a 5% drop in water withdrawal and a similar reduction in greenhouse gas emissions (Fig. 4). While these numbers are considerable, they are less than the food waste reductions suggest. This is because most waste occurs for crops and not for animal products.

Climate policy. A large body of literature exists on climate mitigation policy scenarios leading to a global warming level well below 2 °C[45]. Such scenarios mostly reduce emissions by increasing the efficiency of energy end use, and tackling unabated fossil fuel combustion (especially coal) and replacing it with renewable energy, nuclear power, bio-energy and technologies with CO_2 capture and storage (CCS). The use of bio-energy and CCS represents a key part of the strategy to compensate for near-term emissions in the long-term[23]. Other measures include reducing non-CO_2 emissions, and afforestation. The calculations made here are based on a scenario that stays within a forcing of 2.6 W m^{-2} at the end of the century. This scenario is expected to lead to a level of global warming near 1.7 °C compared with preindustrial levels[23]. As shown in Fig. 4, the nexus linkages are important considerations for climate mitigation policy. Important examples are the impacts of bio-energy on land use and water use, and the reduced need for cooling in thermal power plants[46]. Figure 4 also shows that the other measures discussed above can all lead to reduced greenhouse gas emissions. While we focus on the trends up to 2050 here, it should be noted that further reductions are needed after 2050. In fact, consistent with many scenarios in the literature, carbon dioxide emissions would need to become net negative as a result of the large-scale application of bio-energy and CCS, as well as afforestation. As both options require land, this will further impact the nexus resources.

Integrated analysis and responses needed

The integrated response scenario presented here illustrates the impacts of combining the four options for changing resource use. The integrated scenario assumes the application of all options for change at half their potential, except for the climate policy option, which is kept aiming for the 2 °C target (Table 1). The results of the response scenario are included in Figs. 1–4. Figure 3 connects the previous Sankey diagrams from Fig. 2 by showing how the water, land, crop, animal and energy systems and consumption categories interact and impact each other. Key connections include the use of water in agriculture and energy production, and the use of biomass for energy production. The connections between the different systems provide opportunities to establish trade-offs, and to take advantage of synergies.

If implemented, the integrated response scenario almost meets the challenges of increasing agricultural production to feed 9 billion people, while at the same time reducing pressure on biodiversity. This strategy would also lead to less water consumption than the reference scenario. The integrated scenario is meant to be illustrative, as other combinations of options can lead to similar results if combined appropriately. This analysis shows the need for such integrated responses, but also further integrated analysis of response strategies. Further integrative analysis refers to a broader set of measures (for example, also targeting water-use efficiency), as well as analysis of other aspects of these strategies. Given that the implementation of measures will have a substantial impact on energy and food systems, and may run into resistance, it is important to note that synergies between measures could be crucial when

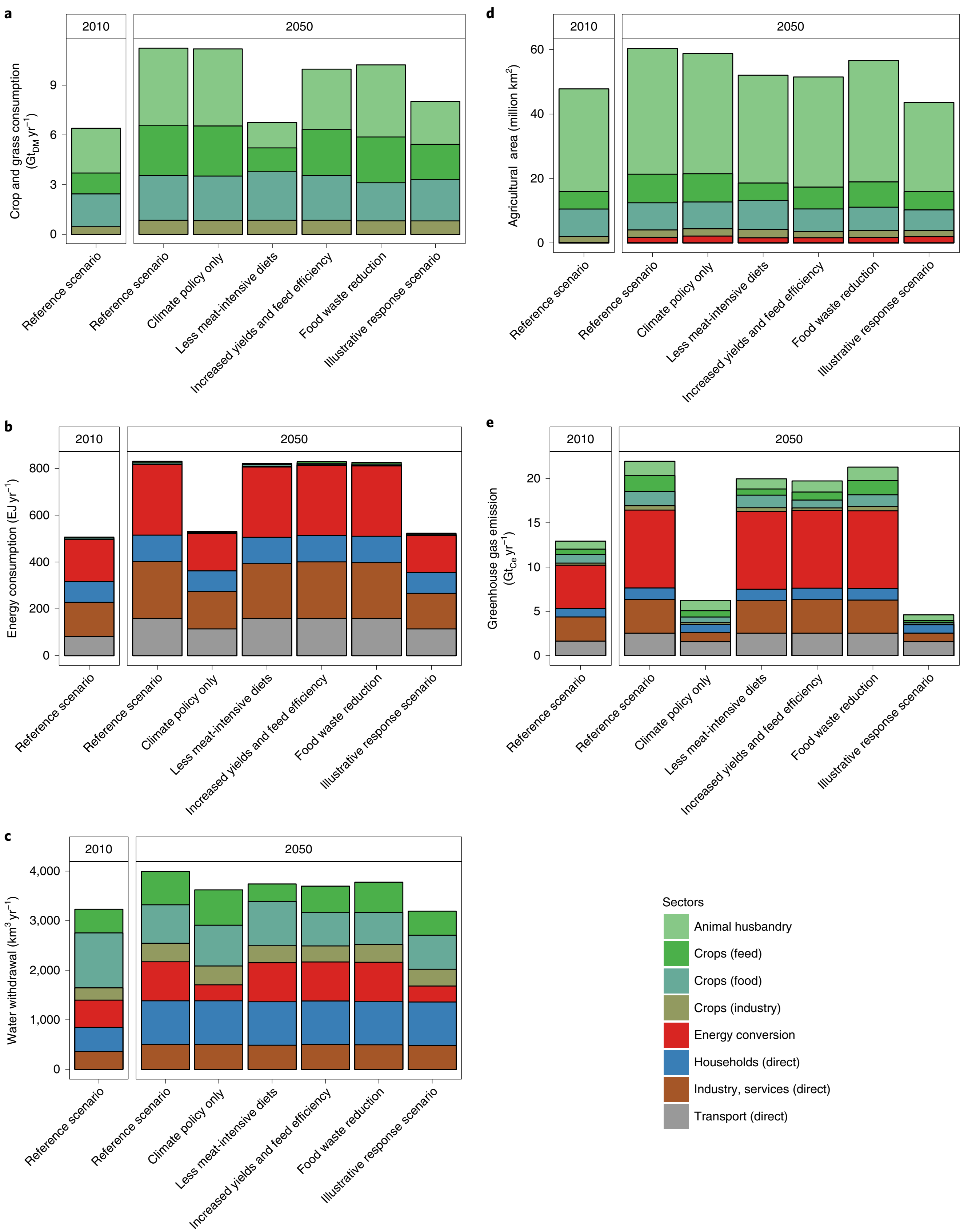

Fig. 4 | Options for change and their impact on resource consumption, land use and greenhouse gas emissions. a–c, Consumption of agricultural products (**a**), energy (**b**) and water (**c**). **d**,**e**, Associated impacts on agricultural area (**d**) and greenhouse gas emissions (**e**). In all panels, the left plot shows the results for the reference scenario projected to 2010, while the right plot shows the reference scenario alongside different options for change and an illustrative response scenario that embraces all four options, projected to 2050.

trying to secure societal support. It should be noted that implementation will involve much more than technology change alone. For example, it also requires a reorientation of investments and technology development towards more efficient use of resources. This means ensuring the involvement of all key actors in society. It also implies that incentive structures should match the selected pathways (for example, to accomplish a dietary change). Also, new technologies could work towards providing feasible, new ways of increasing resource efficiency (for example, alternative sources of protein and smart grids). Further analysis using different tools highlighting economic and socio-political aspects will be important to further look into the feasibility of these transitions. Moreover, as the transitions will take time, action must be taken soon, especially if the implemented measures are to be fully effective before 2030—the target year of the Sustainable Development Goals agenda.

Methods

In this paper, we developed a set of scenarios to explore the nexus relationships between land, energy and water, as well as the associated impacts on greenhouse gas emissions and land use. In the analysis, we used the SSP2 baseline scenario and explored the impact of several response options (chosen on the basis of the suggestions of Foley et al.[20]). The scenarios were developed using a combination of the FDM[37] and IMAGE 3.0 (ref. [21]). Using an integrated assessment model allowed us to explore several key interlinkages between the nexus domains. Here, we discuss the key models and their assumptions, the scenario assumptions and the Sankey diagrams used to present the results.

Models. IMAGE 3.0 was used to calculate changes in land, energy and water use and greenhouse gas emissions. For food demand and production, we used the FDM.

FDM. Consumption. The FDM (described in detail elsewhere[37]) is based on well-known relationships in food demand modelling known as Engel's laws, which state that households with lower incomes spend a larger share of their income on food, but also that absolute expenditure on food increases with income (albeit less than proportionally)[47]. It should be noted that average expenditure per calorie also increases with income, since richer households buy more luxury items, such as coffee and meat products, and spend more on 'value added', such as service in restaurants, or premium packaging and advertising in supermarkets. For the FDM, we established the relationship between six main food categories for 26 world regions on the basis of FAO data[2], using the following equation:

$$D_{r,f} = a_f \times \ln[I_r] + b_f + R_{r,f}\left(\text{kcal capita}^{-1}\right) \tag{1}$$

where I indicates income, D indicates food demand, a and b are parameters describing the dependence on income for different food categories, and R represents regional specifics. Finally, the subscripts r and f refer to regions and food products, respectively. We estimated the global parameters based on the global dataset (all 26 regions together), while, subsequently, the region-specific offset R was introduced. In the calculations, we applied the equation for each region to ten different population segments (based on income and rural versus urban classification), assuming that the income-demand relationships remain fixed over time. This means that the behavioural difference between two points in time for a single population segment (due to increasing income) is the same as the behavioural difference between a poor population segment and a richer population segment at a single point in time. For each of the six major categories, we established roughly linear relationships between food availability (kcal capita^{-1}) and the logarithm of average gross domestic product per capita, referred to elsewhere in the paper as income (see Supplementary Fig. 1). Subsequently, within each food category, minor food categories were defined (for example, different cereal types within the category of staple crops). The consumption of these minor categories was derived by time-dependent, regional fractions. These often reflect specific dietary preferences in regions (for example, beef, goat, pig and chicken consumption within the meat category). Based on the SSP2 storyline, we assumed a very slow converge of these factors to the global average (due to globalization), so that by 2050 about one-third of this process will have taken place. The urban and rural income-based population quintiles, with their corresponding average incomes are consistent with those used in the energy model used in IMAGE, and the FDM was constructed from Gini coefficients using the Atlas method[37,48]. The slope of the global income relationship was then applied to each quintile separately, and the result was recalibrated such that regional average demand exactly matched the data in 2011 (FAO Corporate Statistical Database[2]). This step was necessary due to the nonlinear relationship between food demand and income, which means that the average of population segments' food demands is not the same as the food demand pertaining to the average income. In the model, some additional assumptions were included to deal with special regional characteristics, such as lactose intolerance[37].

Subsequently, household food waste was modelled, using food waste fractions with a log-linear relationship to income, based on estimates from Gustavsson et al.[49], and constrained between the current minimum and maximum waste fractions attained globally for each food. Thus, the waste fractions for various foods increase with income for each population segment (poor populations waste less than rich populations in the same region).

Production levels and feed. As input to IMAGE, the FDM food demand scenarios need to be converted in production scenarios. For this, we used the existing IMAGE SSP2 trade scenario from the IMAGE model. For 2010, the SSP2 IMAGE numbers are fully calibrated to FAO statistics while the trajectory over time is based on the results of the macro-economic agriculture model coupled to IMAGE[23,32]. This scenario was subsequently scaled, by then applying the regional shares of global production from IMAGE for each year[37]. This method can be applied well if the differences between the two demand scenarios (that is, the FDM demand scenario and that of the original IMAGE model) are relatively small and the focus is on global-scale results. At the same time, it should be noted that regional results could be different from a fully coupled agro-economic model (for instance, in terms of changes in the share of regions in global production based on differently shaped production cost curves). Production for animal products was converted further into feed crops and grass production using the IMAGE SSP2 animal feed efficiencies (specified per region, animal product and feed type). Finally, industrial (non-food) demand for food crops was specified per SSP scenario, but was not differentiated for the alternative scenarios.

The FDM allows the exploration of alternative options, such as prescribing alternative diets or exploring the consequences of alternative food waste assumptions[37]. This can be done by substituting animal proteins for plant proteins. For household food waste, alternative product-specific waste fractions can be assumed.

IMAGE 3.0. IMAGE is an integrated assessment model framework that simulates global and regional environmental consequences of changes in human activities. A very detailed model description of more than 300 pages is available online[21]. IMAGE is a simulation model (that is, changes in model variables are calculated using information from the previous time step). The model includes a detailed description of the energy and land-use system and simulates these socio-economic parameters for 26 regions. For environmental parameters, a geographical grid of 30 min × 30 min or 5 min × 5 min is used. The model has been designed to analyse large-scale and long-term interactions between human development and the natural environment, and to identify response strategies to global environmental change based on the assessment of options for mitigation and adaption.

IMAGE is a framework with a modular structure, with some components linked directly to the model code of IMAGE and others connected through soft links (where models run independently with information exchange via data files). The IMAGE framework comprises two main systems (Supplementary Fig. 2): (1) the human or socio-economic system, which describes the long-term development of human activities relevant for sustainable development; and (2) the Earth system, which describes changes in natural systems, such as the carbon and hydrological cycle and climate. The two systems are linked through emissions, land use, climate feedbacks and potential human policy responses. Important inputs to the model are descriptions of the future development of so-called direct and indirect drivers of global environmental change: exogenous assumptions on population, economic development, lifestyle, policies and technology change form a key input into the components calculating energy, food and water demand projections.

Energy. For energy, the energy system model TIMER was used. TIMER describes 12 primary energy carriers in 26 world regions, and is used for analysing long-term trends in energy demand and supply[21,50]. The focus is on dynamic relationships in the energy system, such as inertia and learning by doing in capital stocks, depletion of the resource base and trade between regions. The energy demand is based on relationships between economic activity, energy prices and energy demand. The economic activity levels determining demand are often described in detail, such as for transport (using a detailed transport model)[51], steel and cement production[52] and residential energy demand[48]. Different energy carriers can be used to fulfil the energy demand; their substitution is driven by prices and preferences and is described by multinomial logit equations. The energy supply modules describe the production of primary energy carriers, and calculate prices endogenously for both primary and secondary energy carriers that drive investment in the technologies associated with these carriers. Key dynamics include technology change and resource depletion. Technology change is mostly described by learning by doing, while depletion depends on cumulative production for non-renewable energy carriers, and on actual (annual) production for renewables. The energy flows in all three main components allow for the calculation of greenhouse gas and air pollutant emissions.

Food and land use. For food demand and trade, we used the projections from the FDM. Food production was subsequently allocated to a detailed grid using an empirically based allocation algorithm driven by potential crop yield, population density, accessibility and terrain slope index. The yield for each grid cell was determined for different crop types using the Lund–Potsdam–Jena managed land (LPJmL) model, on the basis of climate and soil characteristics in combination with a regional 'management factor' that describes the observed difference between actual and potential yields. The management factor was calibrated for the historical period on the basis of FAO statistics, and can be used in scenarios to describe progress in farming methods. Typically, the management factor was lower in developing country regions than in developed country regions.

Water. In IMAGE, the hydrological cycle is represented by LPJmL[53,54], which simulates the global hydrological cycle as part of the dynamics of natural vegetation and agricultural production systems. Because LPJmL is directly linked to IMAGE, there is consistency in the way the carbon cycle, natural vegetation dynamics, crop growth and production, land-use allocation and water balance are modelled. Water demand for agriculture is based on assumed changes in irrigation area, and the actual demand per grid cell on the basis of production and climate characteristics. Water demand for power production is based on the actual energy generation characteristics in IMAGE (see 'Energy') in combination with a description of cooling techniques[28]. Demand for industry and residential sectors is based on the trends with, income as described elsewhere[28]. Efficiency of water use is assumed to change over time, consistent with the storyline of the scenario[28].

Greenhouse gas emissions. Greenhouse gas emissions are associated with the energy system, industrial activity, use of halogenated substances, land-use change and agriculture. In IMAGE, the emissions are mostly calculated by multiplying relevant activity levels by emission factors. The emission factors can change over time for methane and nitrous oxide based on technology progress and policy. Here, the settings of the SSP2 scenario were used.

Earth system. In IMAGE, the main interaction with the Earth system occurs with changes in energy, food and biofuel production that induce land-use changes and emissions of carbon dioxide and other greenhouse gases. A key component of the Earth system is the LPJmL model[53,54], which is included in IMAGE 3.0. LPJmL covers the terrestrial carbon cycle and vegetation dynamics in IMAGE 3.0. This model is used for determining productivity at the grid-cell level for natural and cultivated ecosystems, on the basis of plant and crop functional types. Based on the regional production levels and the output of LPJmL, a set of allocation rules in IMAGE determine the actual land cover. The calculated emissions of greenhouse gases and air pollutants are used in IMAGE to derive changes in the concentrations of greenhouse gases, ozone precursors and species involved in aerosol formation on a global scale. Climatic change is calculated as the global mean temperature change, using a slightly modified version of the MAGICC 6.0 climate model[55]. The changes in temperature and precipitation in each grid cell are derived from the global mean temperature, using a pattern-scaling approach. The default IMAGE model takes impacts of climate change (temperature, precipitation and CO_2 fertilization) on both natural ecosystems (growth of biomass) and agricultural systems (the growth of crops and grass) into account via the equations included in LPJmL. Here, however, the impacts on agriculture systems have been excluded in line with the protocol for SSP calculations[32].

Scenario assumptions. *Baseline SSP2 scenario.* The SSP2 scenario (a set of community scenarios for climate change and sustainability issues[32]) was used as the baseline scenario in the analysis. The scenario describes medium development patterns for all key parameters, including population, income, lifestyle and technology. The implementation of the SSP2 scenario described here (based on IMAGE and FDM) was consistent with other SSP2 implementations[32,56]. The way the SSP2 scenario was implemented in IMAGE and FDM has been described in detail elsewhere[23,32]. Roughly, the projection follows in the first decade the middle-of-the-road reference projections of the FAO[57] and International Energy Agency[58]. The projections of the SSP2 scenarios are often contrasted with other SSP scenarios, such as SSP1 and SSP3 (SSP1 represents a world characterized by a more sustainable development-orientated pathway, and SSP3 represents a world characterized by regional competition, slow economic development in developing countries, and slow technology development)[23,32]. The key assumption and some important outcomes of the SSP2 scenario are shown in the Supplementary Information.

Alternative scenarios. Several scenarios were developed here to show the impact of alternative resource use assumptions (in particular, land use). First of all, a set of four scenarios looking into individual options were explored. Second, the options were combined for an integrated response scenario. The integrated scenario assumes the application of all individual options but at half their potential, except for the climate policy option, which is kept aiming for the 2 °C target. In most cases, we implemented the options by changing the model parameters, assuming no macro-economic feedback. While this represents a reasonable estimate of first-order effects, the options would also need to be investigated using models with a better representation of the macro-economic dynamics. Table 1 provides an overview of the key assumptions.

Shifting towards less meat-intensive diets. The low-meat diet scenario used in the paper is based on specific levels of meat consumption recommended by Willett (at Harvard Medical School[59]), as interpreted by Stehfest et al.[36] and implemented as follows: 10.4 kcal cap^{-1} d^{-1} for cattle meat, 16.0 kcal cap^{-1} d^{-1} for pig meat, 32.3 kcal cap^{-1} d^{-1} for eggs, 33.2 kcal cap^{-1} d^{-1} for poultry meat and 13.0 kcal cap^{-1} d^{-1} for fish and seafood. We assume that this diet is implemented worldwide in 2050. More details on implementation can be found in Bijl et al.[37]. Applying this diet globally leads to reduced meat consumption by rich populations while increasing it for the poorest populations up to the recommended level. The consumption of pulses, oil crops, staples and luxuries is adjusted to keep total protein and calories constant, as in the other dietary-change scenarios[37].

Increase agricultural yields and feed efficiency. For the yield-change scenario, we implemented an overall improvement of crop yields of 15% over the SSP2 reference scenario based on the assessment in the IAASTD[42]. In addition, we assumed that it is possible in all regions to implement a 50% convergence to the region with the highest feed efficiency (Western Europe).

Reduce food waste. Kummu et al.[60] used a life-cycle analysis approach, and assumed at each stage of the supply chain and for each food category that the lowest food waste fraction achieved by any region could be achieved by all other regions. Based on this, we also set the current lowest food waste fraction worldwide as a lower bound, for each food category, assuming that all regions approach these numbers exponentially at 10% per year, thus closing the gap by 86% in 2030 and 98% in 2050. For the storage/distribution phase, we assumed all food waste could be avoided (zero lower bound), but at a slower rate of 5% per year, thus reducing the distribution of the food waste fraction by 62% in 2030 and 86% in 2050. These assumptions can be considered as ambitious, and it will be difficult to achieve these waste reductions in practice. More details on implementation can be found in Bijl et al.[37].

Climate policy. Climate policy is introduced in IMAGE by introducing a greenhouse gas emission price that induces changes throughout the system. The price is implemented to reach a radiative forcing of 2.6 W m^{-2} (providing a high chance to stay below 2 °C) in a cost-optimal way. In the energy system, investments are steered towards technologies with no or low greenhouse gas emissions, such as renewable energy, nuclear power, fossil fuels with CCS, and bio-energy. Moreover, end-use energy efficiency is improved as well. For non-CO_2 emissions, all kinds of technologies are introduced that reduce their emissions. This is represented by a decrease in emissions factors. In land use, we assume that policies are introduced to reduce deforestation and increase afforestation. This effort is based on two key measures: (1) increasing protection levels for carbon-intensive ecosystems for more ambitious climate targets (representation of 'reducing emissions from deforestation and forest degradation' policies, leading to reductions of emissions from deforestation and forest degradation); and (2) reforestation of degraded or deforested areas that are not in use for agriculture. The results of this scenario are described in detail elsewhere[23].

Integrated response scenario. The integrated response scenario presented here illustrates the impacts of combining the four options for changing resource use. The integrated scenario assumes the application of all options for change at half their potential, except for the climate policy option, which is kept aiming for the 2 °C target.

Sankey diagram representations. Sankey diagrams[24,25] are flow diagrams in which the widths of the arrows are proportional to the flow quantity. Key leverage points can be emphasized in the diagram where the system can be made more sustainable. In each figure, a comparison is made between the reference scenario and a response scenario (as is described in more detail in this paper). The Sankey diagrams are generated on the basis of the supply and demand flows of the IMAGE model. End-use efficiencies in energy are somewhat difficult to define based on different interpretations of boundary conditions (for example, heating efficiency in houses). Additional efficiency parameters have been used to indicate the efficiency losses in this stage of the chain, based on existing values in the literature[1]. The results represent the efficiency losses at this stage as well.

Data availability

The data relating to the scenarios described in this paper are available for download from https://models.pbl.nl/image/index.php/Download. The data supporting the figures are available from the IMAGE website at PBL (https://go.nature.com/32CZSLh).

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Author contributions

D.P.V.V. and D.L.B. designed the experiments. All authors contributed to the scenario analysis and the writing of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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