Multi-target scenario discovery to plan for sustainable food and land systems in Australia

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Abstract
The development of detailed national pathways towards sustainable food and land systems aims to provide stakeholders with clarity on how long-term goals could be achieved and to reduce roadblocks in the way to making commitments. However, the inability to perfectly capture the relationships between all variables in a system and the unknown probability of future values (deep uncertainty) makes it very difficult to design scenarios that account for the full breadth of system uncertainty. Here we use scenario discovery to systematically explore the effect of different parameter ranges on model outputs, and design resilient pathways to sustainability in which multiple target achievement requires a broad portfolio of solutions. We use a model of the Australian food and land system, the FABLE (Food, Agriculture, Biodiversity, Land-use, Energy) Calculator, to investigate conditions for achieving a sustainable Australian food and land system under scenarios based on the Shared Socioeconomic Pathways (SSP) 1, 2, and 3 narratives. Here we link the FABLE Calculator with a Monte Carlo simulation tool to explore hundreds of thousands of scenarios. This allows us to identify the ranges of systemic drivers that achieve multiple sustainability targets around diets, net forest growth, agricultural water consumption, greenhouse gas emissions, biodiversity conservation, and exports by 2050. Our results show that livestock productivity and density, afforestation, and dietary change are powerful influencers for sustainability target achievement. Around 10% of the SSP1 scenarios could achieve all modelled sustainability targets. However, practically none of the scenarios based on SSP2 and SSP3 narratives could achieve such targets. The results suggest that there are options to achieve a more sustainable and resilient Australian food and land-use system with better socio-economic and environmental outcomes than under current trends. However, its achievement requires significant structural changes and coordinated interventions in several components of the domestic food and land system to increase its resilience and environmental and socio-economic performance. Understanding the bounds within which this system needs to change and operate to achieve sustainability targets will enable greater clarity and flexibility during discussions between decision-makers and stakeholders.

Keywords Scenario discovery · Agriculture · Land use · Decision support · Drivers · Stakeholders · Food policy
Introduction

Contemporary food and land systems are highly vulnerable to environmental, economic, and institutional pressures that limit their capacity to fulfil societal needs sustainably. The agricultural Green Revolution of the 1960s contributed to widespread reductions in poverty and hunger due to policies that promoted rapid intensification of production. These same policies led to overuse of inputs and other practices that eroded our natural resource base (Pingali 2012), increased greenhouse gas emissions from crop and pasture lands (Foley et al. 2011; Godfray et al. 2010; Tilman et al. 2011), altered the natural Nitrogen and Phosphorus balance (Canfield et al. 2010; Damme et al. 2018; MacDonald et al. 2011; Withers et al. 2014), and increased the toxicity impacts on humans (Bahrami et al. 2017; Chowdhury et al. 2013; Kim et al. 2017) and wildlife (Baron et al. 2017; de Castro-Catala et al. 2016; Dubey et al. 2020; Navarro et al. 2021; Schreinemachers et al. 2020; Stehle and Schulz 2015). The continuation of this trend is unsustainable, which means business-as-usual (BAU) policies and practices will need to be reconsidered if we are to meet future national and global goals around food and land system targets. Identifying potential outcomes of alternative food and land pathways\(^1\) requires careful consideration due to the uncertain nature of socio-economic, environmental, technological, and political variables. Failure to account for such uncertainties could increase the risk of implementing ineffective solutions to sustainability issues (e.g. wrong timing or scale of efforts) (Kwakkel et al. 2016). These setbacks increase when the assessments of plausible pathways require modelling of interactions between domestic and global uncertainties (e.g. land-use policies, water use efficiency, climate change abatement efforts, and dietary trends).

Integrated assessment models (IAMs) have been extremely useful in food and land system analyses to investigate the effects of policies and widespread practice changes and to understand complex system responses by simultaneously considering institutional, environmental and human contexts (Hamilton et al. 2015). International efforts to coordinate their parameterisation, harmonise input data, and address issues around their basic assumptions have been underway for several years (Lampe et al. 2014; Rosenzweig et al. 2013, 2018). Multiple scenario techniques based on IAMs have been developed to improve our understanding of the impact of parametric or system uncertainty in sustainability research (see Guivarch et al. 2017 for a comprehensive review). Some of those techniques have been applied in food and land systems research, e.g. Monte Carlo Simulation (Valin et al. 2015), global sensitivity analysis (Gao and Bryan 2017; Gao et al. 2016), story-and-simulation (Brinsmead et al. 2019; Hatfield-Dodds et al. 2015). However, complexities associated with implementing IAMs (e.g. computational requirements, learning curve) limit their use at national scale and for exploring many scenarios representative of the input parameter space (i.e. the space of possible values of the parameters that define a mathematical model). Therefore, results from IAMs cannot be easily linked to decision-making (Ackerman et al. 2009; Nelson et al. 2014; Vuuren et al. 2011).

Scenario discovery is a term that describes a range of statistical and data-mining techniques used in the field of decision-making to aid the identification of conditions required to achieve or avoid specific policies. Scenarios are valuable to support decision-making through the comparison of alternative actions’ impacts on the evolution of key objectives. However, in the presence of deep uncertainty, i.e. the inability to model all relationships between variables and the different probabilities of input parameters, it can be misleading to rely on a reduced number of scenarios that cannot capture the full breadth of uncertainty about the future (Kwakkel et al. 2016). Scenario discovery techniques can handle combined uncertainties of multiple input parameters to reveal regions in the input parameter space that produce results of interest to policymakers. Scenario discovery, therefore, enables us to work with deep uncertainty in a rigorous way by systematically exploring the effect of different parameter ranges on simulation outputs (Moallemi et al. 2020) and dependencies between parameters and model outputs.

Here we demonstrate the relevance of scenario discovery analysis (Bryant and Lempert 2010) to underpin scenario definition for food and land systems. We use scenario discovery to identify an input parameter space from which we can define resilient transition pathways towards sustainability in the food and land system. We define a resilient pathway as one which requires a diversified portfolio of solutions working together to hit multiple targets, rather than over-relying on small sets of solutions or individual levers (e.g. afforestation, carbon capture and storage) which increases the risk of setbacks. We also investigate the conditions that could lead to achieving country-level food and land system targets and the feasibility of achieving multiple targets when these are dependent on multiple parameters. The analysis relies on an empirical model of the Australian food and land system based on the FABLE (Food, Agriculture, Biodiversity, Land-use, Energy) Calculator (Mosnier et al. 2020). The FABLE Calculator is an open-source equilibrium model supporting the FABLE Consortium’s efforts to investigate globally coordinated national pathways towards sustainable

\(^1\) The term pathways is defined in this paper as the set of conditions for key variables of the food and land-use system under which sustainable goals can be achieved. We do not explore the set of actions required to achieve such goals.
Food and land systems. Around 30 scientists from 20 countries have collaborated in the development of this tool to allow flexible representations of national food and land system and historical system dynamics more accurately. As a result, the FABLE Calculator allows agile and transparent analysis of trade-offs and opportunities of pathways to sustainable food and land system futures.

In this analysis, we explore Australia’s capacity to meet multiple sustainability targets by 2050 under scenarios based on the shared socioeconomic pathways (SSP) 1, 2 and 3 narratives (O’Neill et al., 2017). SSP1 represents a sustainable future with global cooperation, rapid technology development, strong environmental policy, and low population growth with more sustainable consumption and production. SSP2 represents a continuation of long-term trends and SSP3 represents a future where there is a lack of international cooperation to tackle global issues, and environmental and social goals are not a priority (O’Neill et al., 2017). Within each set of SSP scenarios, we modelled plausible realisations of parameters influencing the quantity and environmental footprint of agricultural production. The scenario parametrisation is based on an initial exploratory analysis on six hundred thousand samples from empirically defined ranges of input parameters. Outcomes of each scenario were computed using the Australian FABLE Calculator (FABLE Consortium 2020) linked to scenario discovery methods to identify the most influential parameters for meeting sustainability targets. This modelling approach is important when it comes to supporting long-term thinking and target-focused strategies to solve problems that require the coordination of national efforts and the flexibility to adapt to changing environmental, socio-economic, and political conditions.

Materials and methods

Study area

Agriculture is one of Australia’s most important industries, contributing about 3% of Australia’s GDP or $60bn AUD per annum (Marinoni and Navarro 2018; NFF 2017), and directly employing 304 thousand people across 86,000 farms. In 2010, the top ten land-uses in terms of total revenue were beef cattle, sheep, dairy cattle, winter cereals, grapes, vegetables, cotton, rapeseed/canola, winter legumes (chickpeas and fava beans), and stone fruit (Navarro et al., 2021). Australia is a net exporter of agricultural produce, each year producing enough food to feed 51 million people worldwide (NFF 2017). For example, in 2019, Australia ranked second, third and fourth in total world exports of sheep, beef and wheat, respectively (FABLE Consortium 2019). In 2010, around 54% of the total land in Australia was used for grazing, 23% for nature conservation, 4% for crops, and 2% for forestry (FABLE Consortium 2020) (Fig. 1).

Over the last 50 years, Australian climate conditions have worsened for agricultural production. There has been a 16% decline in April to October rainfall since 1970 and a 20% decline in May to June rainfall (CSIRO 2020), which has direct consequences for winter crop development and yields. Many areas have seen declining trends in total annual rainfall over the same period. Current projections are that Australia will continue to see increases in heat extremes (affecting plant development) and a continued decrease in cool season rainfall across swathes of southern and eastern Australia (CSIRO 2020) where most agricultural production occurs. The State of the Climate 2020 report predicts this will lead to more time in drought and more intense heavy rainfall events (CSIRO 2020). While the increased incidence of droughts and a general decline in growing conditions have resulted in productivity growth of near 1% p.a. (FABLE Consortium 2020), other studies have found grain farmers, through technical improvements, have only been able to raise yields enough to compensate for the negative effects of climate change since 1990 (Hochman et al., 2017).

Simulation model: the FABLE Calculator

The FABLE Calculator version 2020 (Mosnier et al., 2020) is an Excel-based model designed to compute the potential evolution of food and land systems from 2000 to 2050 in 5-year time steps. It tests the impact of different policies and changes in the drivers of these systems through the combination of a large number of scenarios. Outcome variables include the levels of agricultural production for 76 raw and processed agricultural products for the crop and livestock sectors, as well as changes in crop and pasture area, land-use change (deforestation, afforestation, reforestation, conversion of other natural lands), changes in biodiversity indicators, carbon emissions/sequestration, imports, exports, and water use.

The Calculator is based on computational steps and does not use optimisation techniques. The computation of the annual demand for human consumption is the first step of the FABLE Calculator, i.e. the underlying assumption is that human demand for agricultural products is the key driver of change in food and land-use systems. Human demand has three components: food, biofuels, and other non-food consumption. The computation of the production from the livestock sector is derived from the estimation of the demand.

2 https://www.foodandlandusecoalition.org/fable/.

3 The FABLE Calculator version 2020 is available at https://www.abstract-landscapes.com/fable-calculator.
and the assumptions on trade and productivity. Livestock herd number and consumption of other agricultural products are also computed. Total crop production is based on the computed demand and the projected evolution of post-harvest losses, imports, and exports. The harvested area depends on the assumptions on the evolution of crop productivity and harvesting intensity. The feasible consumption and production levels can be different from the targeted levels if limits on land expansion are met, either because of land scarcity or because of policy constraints on the conversion of natural land to agriculture. Final import and export value might also be different after global trade balance is enforced (FABLE Consortium 2019). The Calculator has been utilised in two international modelling exercises to investigate global pathways towards sustainable land-use and food systems (FABLE Consortium 2019, 2020).

The FABLE Calculator version 2020 relies on multiple assumptions, parameters, and interconnections that spread within different worksheets. The version used in this analysis contains (1) three worksheets dedicated to defining parameters for different scenarios; (2) seven worksheets dedicated to reporting end-point output variables around food intake, GHG emissions, total production, trade, biodiversity, land-use, and water; (3) nine worksheets dedicated to performing calculation steps that translate input parameters into model outputs (plus nine worksheets with supporting information); (4) 23 worksheets containing historical data from FAO and other Australian sources which provide default values used throughout the Calculator. These worksheets host a total of 165 Excel tables, the values of which can be accessed dynamically via thousands of formulas. This means any solution for performing stochastic simulation on the Calculator needs to automatically vary selected parameters within selected bounds and trigger the update of the entire Calculator, so the change in outputs can be tracked and stored. Here we used the software ModelRisk (Vose Software 2020) to perform this task. ModelRisk is a Monte Carlo simulation software that expands Microsoft Excel capability by providing wrapper formulas to define input and output variables and define probability distributions to

![Australian land-use types and ecoregions in 2010 (based on the Australian land-use map 2010–2011; ABARES 2016). In this figure, conservation land corresponds to protected areas, grazing corresponds to grasslands, and the category other corresponds to other lands with minimal human use.](image-url)
convert deterministic cells into random variables. We used this tool to estimate the outcomes of hundreds of thousands of input parameter combinations. In a machine running Windows Server 2016 with an Intel Xeon CPU E5-4640 @ 2.4 GHz and 64 GB of RAM, each combination is evaluated in 1.6 s, with 100 thousand runs taking approximately 8 h.

**Scenario discovery**

Social and economic changes can significantly impact land and food systems, so it is important to carefully select the parameter space explored to focus stakeholder attention on policy-relevant ranges. The method we present here allows us to explore the effects of parameter ranges on all output variables and avoid parameter ranges that result in unrealistic scenarios or non resilient pathways. The implementation of the Monte Carlo simulation over the FABLE Calculator automatically selects random values for multiple input parameters and registers the values of multiple output variables. Through this approach, it becomes feasible to produce tens of thousands of runs in a short amount of time. The simulation was performed in two stages. First, we allowed all parameters to vary randomly (uniform distribution) and independently of each other, with minimum and maximum values derived from empirical data and previous analyses (Brinsmead et al. 2019; Hatfield-Dodds et al. 2015) (Table 1). We then analysed the first set of results to identify parameter ranges that produce unrealistic interactions between parameters and outputs and defined a parameter space that avoids those conditions. In the “Results” section, we describe three examples where land expansion, livestock productivity growth and afforestation needed to be constrained to ensure the scenarios remained realistic (Figs. 2, 3). The new parameter ranges were divided equally into three SSP scenarios based on the SSP scenario narratives (Table 2, not based on the values in the SSP database), and a new simulation was run where parameter ranges were representative of plausible variations of the modelled SSP scenarios. In the scenario parametrisation (Table 2), the values of variables like food waste or post-harvest loss (food

| Scenario parameter bounds       | Min  | Mid                | Max                | Historical reference                              |
|--------------------------------|------|--------------------|--------------------|--------------------------------------------------|
| Population growth (% p.a.)     | 0.8% | –                  | 2%                 | 1.7% (ABS 2018)                                   |
| Alternative diets in 2050      | 1 (fat diet—unhealthiest) | 2 (no change)     | 4 (eat lancet—healthiest) | (FAO 2021)                                       |
| Food waste in 2050 (%)          | 15%  | –                  | 35%                | 30% (Bajželj et al. 2014)                         |
| Agricultural expansion         | 1 (free expansion of ag. land) | 2 (no deforestation beyond 2030) | 3 (no ag. land expansion after 2010) | Free expansion                                   |
| Afforestation (Mha planted by 2050) | 0    | –                  | 19                 | 0.8 Mha growth 2011–2016 (Montreal Process Implementation Group for Australia 2018) |
| Level of physical activity in 2050 | 1 (sedentary) | 2 (moderately active lifestyle) | 3 (active lifestyle) | –                                                 |
| Change in water consumption 2010–2050 | ½ water use (relative to 2010) | –                  | ×1.5 water use (relative to 2010) | (FAO 2021)                                       |
| Climate change impacts on agricultural productivity | 1 (RCP 2.6) warming of ~2 degrees C by 2100 | 32 (RCP 4.5) warming of ~2.4 degrees C by 2100 | 64 (RCP 8.5) warming of ~4.3 degrees C by 2100 | –                                                 |
| Crop productivity growth (% p.a.) | −0.5% | –                  | 3%                 | 0.75% (FABLE Consortium 2020) based on (Marinoni et al. 2012) |
| Livestock productivity growth (% p.a.) | −0.5% | –                  | 3%                 | 1.25% (FABLE Consortium 2020) based on (Marinoni et al. 2012) |
| Livestock density growth (% p.a.) | −0.5% | –                  | 3%                 | 0.3% (FABLE Consortium 2020) based on (FAO 2021) |
| Export growth by 2050           | ½ exports (relative to 2010) | –                  | ×2 exports (relative to 2010) | –                                                 |
| Import growth by 2050           | ½ imports (relative to 2010) | –                  | ×2 imports (relative to 2010) | FAOSTAT Detailed Trade Matrix (FAO 2021)          |
| Post-harvest losses in 2050 (%)  | 0    | –                  | 3%                 | 0.69%                                            |
loss) are linked to the SSP scenario. For example, food waste in SSP3 can vary between 35 and 25% and food waste in SSP2 can vary between 30 and 20%. However, productivity-related parameters (crop/livestock productivity growth, livestock density growth) are not linked to scenarios (i.e. the value range is the same for all three scenarios) to reflect the real-world uncertainty around our ability to control these outcomes of public policy and technological development.

Defining economic and environmental targets

Based on outcomes of the sample of plausible pathways of the Australian land-use and food systems, we identified regions of the input parameter space where combinations of sustainability targets were achieved by 2050. Five environmental targets were defined as follows:

- **Food consumption.** Average kilocalorie consumption per capita that was greater than or equal to the average Minimum Dietary Energy Requirement (MDER) of the level of activity assumed under each scenario at the national level.
- **Net afforestation.** Net forest growth of at least 400,000 ha by 2050. This is equivalent to the net forest growth observed from 2010 to 2018 (DISER 2020).
- **Water consumption.** Irrigated water consumption that was lower than or equal to that observed in 2010, a period...
of very high water conservation following the Millenium Drought (Aghakouchak et al. 2014).

- Net-zero emissions. Net-zero emissions from agriculture and land use and land-use change by 2050.
- Biodiversity conservation. At least 50% of the Australian landmass supports biodiversity conservation (e.g. regions with marginal use for productive activities such as agriculture or mining).

Around 70% of the Australian crop and livestock production is exported (ABARES 2021b). Agricultural exports are critical for rural economies and a significant driver of land-use decisions (Marcos-Martinez et al. 2017). Therefore, the design of sustainability policies for land and food systems requires careful consideration of potential impacts on export values. From 2010 to 2014, the value of Australian exports increased around 25% relative to 2010 (ABARES 2021a). Afterwards, export values have remained around $50 billion Australian dollars per year. While a record increase in exports of around 12% is expected for the crop year 2021–2022, high rates of export growth are usually driven by temporary poor growing conditions in other countries and high prices (ABARES 2021a). At the time of writing this manuscript, short- to long-term impacts of the COVID-19 pandemic and the conflict between Russia and Ukraine on food prices and trade were difficult to robustly assess quantitatively. The Australian Farmers Federation has set a target to achieve $100 billion in agricultural output by 2030 (DAWE 2021), which is two times the export value observed in 2010. While a similar change in export value...
may be expected, we assume a less ambitious target with at least 50% increase in the 2010 export value by 2050.

We filtered scenarios where all or some of these targets were achieved to create clusters of successful sustainability pathways. Within each cluster, the range of each stochastic input parameter was calculated to identify key parameters for policy design.

Results

Stage 1: defining SSP parameter space

This first stage of the analysis comprised over 600,000 model runs to ensure a thorough exploration of the broad parameter space (Table 1). We then performed an exploratory analysis of the model results to visualise the relationships between variables. During this exploratory analysis, we discovered that certain parameters needed to be limited to ensure the scenarios remain realistic. For example, Fig. 2 shows how the land expansion and livestock productivity parameters affect the relationship between crop productivity growth and feasible production value in 2050. Australia has a large area of marginally productive land. Hence, when the land expansion parameter allows agricultural land to expand, modelled agricultural production requirements (based on internal demand and exports) do not depend on crop productivity growth to be met. When strong constraints on the agricultural land expansion parameter are introduced in the model, higher livestock productivity values can free some pastureland which becomes available for crop area expansion, thus reducing the need for higher crop productivity to achieve the production requirements. Note that in reality the capability of land to support production of pastures, broadacre, and horticultural crops is dependent on local soil and climate conditions, and, therefore, a hectare of freed pasture may or may not be suitable for, e.g. cereal or horticultural production. In Australia, large portions of pastureland are of low capability and, therefore, not suitable for cropping. When the land expansion parameter is restricted to no further expansion beyond 2010 values, and when the livestock productivity growth parameter does not increase beyond historical growth rate (1.25% p.a.), changes in crop productivity are correlated with feasible food production (Fig. 2). Given crop areas have been either declining or stagnant nationally in recent decades (Figure S1), allowing parameter values that cancel the effect of crop productivity growth on total production value would result in unrealistic model dynamics.

Similarly, the exploratory analysis revealed that afforestation parameter values well above 4.75 million hectares render gains in livestock productivity irrelevant to net GHG emissions (Fig. 3). Limiting the afforestation parameter to no more than 5 million hectares ensures our analysis remains realistic given the Australian policy environment since 2012 and climate-driven disasters in recent years: the future adoption of carbon/environmental plantings based on current schemes like the Emissions Reduction Fund (DISER 2022) is unknown, and future plantings could be affected by incidence of bushfires, floods or droughts and result in setbacks of total area afforested. Based on the exploratory analysis, we defined limits to each parameter to focus the second stage of the analysis on a reduced parameter space. Table 2 provides the resulting parameter ranges, divided into SSP scenarios. These were used to generate a further 200,000 model runs.

Stage 2: exploring the SSP parameter space

A correlation matrix provides some insight into how 29 input parameters and output variables in the Calculator relate to each other (Fig. 4). Input parameters are at the top, and output variables are at the bottom of the chart. The values and colour transparency represent the 1:1 Pearson correlation between variables, rounded to the first decimal (values below 0.05 are set to 0). Positive correlations are coloured blue, and negative correlations are red. The relationship between input parameters and output variables are key to gaining insight into whether the model parametrisation results in sensible interactions, to spot potential issues, and to gain insights into more complex interactions within the model. For example, during the development of this method, Fig. 4 enabled us to gain insight into the parametrisation of the FABLE Calculator resulting in no correlation between crop productivity and outputs like production value (Fig. 2) or exports. An inset provides an illustrative example of what lies beneath a correlation coefficient and succinctly highlights how the correlation coefficient is a simplification of complex dynamics.

The total GHG emission variable is correlated with many parameters, including climate change impacts on crop productivity, national diets, food waste, and post-harvest losses. However, many of these parameters are dependent on each other through the SSP scenario parametrisation (Table 2). In fact, the main explanatory variables for GHG emissions are the afforestation and livestock productivity growth parameters, whereas parameters like food loss and food waste matter less due to Australia’s status as a net exporter. The national diet parameter has a limited influence over other output variables due to the strong influence of exports, but adoption of the average EAT-Lancet diet (i.e. national diet parametrisation based on the EAT-Lancet diet) does have the potential to influence outcomes strongly, in a way that current diets cannot (Fig. 5). Higher livestock productivity growth parameter values (for the same demand) means less land is required for pastures, which allows this land to go
out of production and to have the potential to regrow vegetation. The correlation between livestock density parameter and total GHG emissions is zero because emissions follow different trends depending on the sign of livestock density growth (emissions tend to increase if livestock density growth < 0 and tend to decrease otherwise) (Fig. 6). It is another example of how parameter ranges affect the correlation between variables because the correlation coefficient simplifies complex dynamics.

The scenarios for population activity and export growth completely explain the variation in the dietary kilocalorie target and the export target (correlation of 1). The MDER that we use as a minimum boundary for the dietary target is determined by population structure by age class and sex and the average population activity level. Yet, only the population activity level varies across scenarios in the FABLE Calculator. Exports are exogenously determined and the only difference that can occur between export targets and feasible exports is when the production requirements cannot be met. The level of imports is entirely controlled by the import scenario/parameter, and the scenarios that impact the level of the internal demand such as the national diet and food waste. The percentage of land that supports biodiversity is not only most strongly determined by livestock productivity growth and density parameters but also influenced by exports and the national diet scenarios (those impact the level of agricultural land abandonment which is assumed to be able to support biodiversity conservation), and the afforestation parameter.

With export parameter values in 2050 between the level observed in 2010 and twice that amount (i.e. no export target set), around 41% of the scenarios associated with SSP1 achieve all five assessed sustainability targets by 2050. The percentage is significantly reduced under SSP2 (4%).
Achieving any combination of three sustainability targets was feasible in at least 41% of the assessed scenarios. When emission reduction and biodiversity conservation land targets were not included, such a percentage increased to 85%. This increase is caused by the wide range of possible values of livestock density growth on pasturelands. Both livestock productivity and density growth have a strong influence over total GHG emissions and the amount of conservation land because they directly influence the modelled amount of pasture that is converted to Other Land and available for natural vegetation regrowth (Fig. 4). However, low or negative values of livestock density growth make it quite likely to miss emission reduction and conservation targets (Fig. 7), which is why we see a jump in percentage when those targets are not enforced. The scenarios achieving at least three targets ranged from 4 to 53% for SSP2 and 0.5–24% for SSP3. On average, achievement of any two targets under any SSP occurred in 34% of the assessed scenarios, but there is a decreasing chance of meeting three or four targets simultaneously, 22% and 17%, respectively. Meeting more than three targets in the SSP3 scenario is uncertain and depends highly on the set of targets, but in general, there is little to no chance of meeting three or more targets simultaneously (up to 15% at most).

Once exports are required to be at least 1.5 times the 2010 values, the likelihood of achieving at least three targets is
impossible to meet the water consumption target (<0.3% of)

The combination of the export target and SSP3 makes it

The percentage of model runs that meet all targets tends to grow signifi-

under SSP1 and zero under SSP2 and SSP3. The percentage

Fig. 7 Density plot of livestock productivity vs percentage of land

almost zero under SSP2 and SSP3 scenarios and around 14% under SSP1 conditions. The percentage of scenarios that

The combination of the export target and SSP3 makes it

the last row of Table 3. Figure 8 shows what parameter

We now investigate what are the conditions compatible with the achievement of our five sustainability targets, i.e.
In Fig. 5, widespread adoption of the Fat Diet makes it as well unlikely to meet the GHG emission target, but not impossible (the adoption of EAT-Lancet does not guarantee success either, even though it is very influential). Similarly, for all climate change projections linked to SSP1 and SSP2, there were combinations of improvements in crop and livestock productivity, afforestation, and other variables that could counteract modelled yield impacts.

Afforestation in SSP2 scenarios ranges between 1.5 and 3 million ha, and there is no change in diets. Both of these factors place more pressure on other modelled variables to achieve sustainability targets. Gains in livestock productivity per year need to be at least 1.1% per annum.

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**Fig. 8** Feasible parameter space to achieve all sustainability and export targets. Transparent bars indicate that targets could be achieved within the modelled range.

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| SSP1 |   |   |   |   |   |   |   |   |   |
|------|---|---|---|---|---|---|---|---|---|
|      |   |   |   |   |   |   |   |   |   |

| SSP2 |   |   |   |   |   |   |   |   |   |
|------|---|---|---|---|---|---|---|---|---|
|      |   |   |   |   |   |   |   |   |   |
(similar to historical gains) from 2010 to 2050 (Table 1), and livestock density needs to increase at least by 0.5% per year (Fig. 5), which is 0.2% greater than historical change. The range of imports and crop productivity is also smaller than the observed in SSP1 scenarios, which indicates imports become more influential in SSP2 scenarios. No SPP3 scenarios could achieve all the modelled targets.

Interactions and trade-offs between food and land system components can be observed in the results of scenarios that achieve all modelled environmental and export targets. Overall, the results are consistent with SSP narratives indicating a more sustainable future in SSP1 scenarios than under SSP2 and SSP3 conditions (Table 4). SSP1 scenarios have the largest median reduction in CO₂e emissions (35 MtCO₂e) and net forest expansion (4 million ha), GDP (4% p.a.) and population growth (1.39% p.a.). Consistent with a moderately active lifestyle, median daily kilocalorie consumption in SSP1 scenarios was 2851 kcal. Livestock productivity and density in SSP1 required around half the median increments per annum estimated for SSP2 scenarios. This was potentially due to other conditions contributing to achieving sustainability targets, e.g. larger afforestation in SSP1 than SSP2. No single parameter combination under SSP3 conditions could achieve environmental and export targets.

Table 4 Minimum, maximum and median of modelled variables for scenarios achieving environmental and export targets

| Variable | SSP1 | | | SSP2 | | |
|----------|------|---|---|------|---|---|
|          | Min  | Median | Max | Min  | Median | Max |
| Agricultural CO₂e emissions (MtCO₂e) in 2050 | −91.55 | −34.86 | −0.03 | −10.50 | −3.25 | −0.25 |
| Net forest expansion (1000 ha, cumulative 2010–2050) | 3,000 | 4,061 | 4,999 | 2,052 | 2,805 | 2,992 |
| Blue water use-crops (% of 2010 value) | 123% | 147% | 160% | 136% | 146% | 152% |
| Blue water use-livestock (% of 2010 value) | 88% | 102% | 149% | 132% | 141% | 150% |
| Level of activity of the population. 1 = low (sedentary lifestyle), 2 = middle (moderately active lifestyle, walking 2.5-5 km per day), and 3 = high (active lifestyle, walking more than 5 km per day) | 2 | 2 | 3 | 2 | 2 | 3 |
| Diets (daily kilocalorie consumption) | 1852 | 2352 | 2852 | 2851 | 2852 | 2852 |
| Minimum dietary energy requirement (kcal) | 1852 | 1852 | 2078 | 2078 | 2078 | 2335 |
| Reduction of food loss during transportation and storage (change relative to 2010 values) | 10% | 15% | 20% | 15% | 20% | 23% |
| Share of food consumption wasted | 15% | 20% | 25% | 20% | 23% | 30% |
| Imports (ratio of 2050–2010 value) | 70% | 140% | 200% | 78% | 162% | 196% |
| Exports (ratio of 2050–2010 value) | 150% | 167% | 200% | 150% | 155% | 162% |
| Share of the land area supporting biodiversity conservation | 50% | 67% | 74% | 57% | 59% | 64% |
| Crop productivity (% increase p.a.) | −0.50% | 0.43% | 1.25% | −0.44% | 0.45% | 1.18% |
| Livestock productivity (% increase p.a.) | −0.50% | 0.75% | 1.25% | 1.09% | 1.20% | 1.25% |
| Livestock density (mean % annual change) | −0.50% | 0.56% | 1.25% | 0.54% | 1.06% | 1.24% |
| Climate change projection | RCP2.6 | RCP4.5 |
| Population growth (% increase p.a.) | 1.27% | 1.39% | 1.51% | 1.03% | 1.08% | 1.26% |
| GDP growth (% increase p.a.) | 3% | 4% | 4% | 2% | 2% | 3% |

No scenarios achieved the modelled environmental and export targets by 2050 under SSP3

Discussion

Here we have demonstrated the value of multi-target scenario discovery to identify conditions that could lead to resilient pathways towards sustainable food and land systems. We consider a scenario as resilient when it relies upon a diversified portfolio of solutions rather than on a few highly influential variables that can single-handedly determine sustainability targets. For example, our analysis shows that scenarios with afforestation over five million hectares achieve net-zero emissions in the land sector by 2050 regardless of what happens with productivity, livestock density or diets. When the expansion of the agricultural frontier is allowed, declines or marginal productivity improvements do not impact the ability of the Australian food and land system to fulfil domestic demand and exports. Similarly, livestock productivity increases greater than 1.25% p.a. make the impact of crop productivity on sustainability targets almost irrelevant. Whether or not it is realistic to assume afforestation greater than 5Mha, on-demand agricultural land expansion, or productivity increases greater than 1.25% p.a., reliance on single-variable solutions increases the risk of failing to achieve sustainability targets. We argue that resilient pathways require that we diversify the portfolio of solutions to ensure options to compensate for unexpected changes in some variables that could compromise target
achieved. Therefore, discussions with stakeholders will be most fruitful if we keep the parameter space within a region where meeting multiple economic and environmental targets relies on improvements in several areas. Effectively delimiting the parameter space to this region requires the sort of stochastic simulation that we present here. Our prior experience with experts on issues like crop and livestock productivity or afforestation indicates that it is possible to explain historical trends but almost impossible for them to accurately determine long-term values for such variables.

**Resilient pathways to sustainable food and land-use systems**

The results give an indication of the conditions needed to achieve sustainable food and land system targets, or sets of them, under different scenarios based on the Shared Socio-economic Pathways narratives and empirical assumptions about plausible socio-economic, technological, and environmental futures. The results show only around one in ten SSP1 scenarios achieved all five environmental and export targets. Under SSP2 and SSP3 narratives, it was practically unfeasible to reach such targets.

Multi-target achievement was more frequent as key input variables reflected more ambitious policy or societal change (e.g. larger increases in livestock productivity or afforestation, or adoption of healthy and sustainable diets) or as the number of competing targets decreased. This is consistent with research highlighting that improvements in all environmental and economic fronts are very difficult to achieve (Gao and Bryan 2017). Significant change may, therefore, require transformational innovation or greater adoption of multiple existing technologies (Herrero et al. 2020). Regardless, the magnitude of the resources needed to achieve substantial improvements in all six targets simultaneously should not be underestimated.

The results show that livestock productivity and density, afforestation, and dietary change are critical to achieving sustainability targets. Investment in these areas could have wide-reaching knock-on effects that enable Australia to perform better on the exports and environmental fronts. For example, reduced pasture requirements from increasing livestock productivity (or reduced demand) mean more land could support biodiversity and vegetation regrowth. A combination of institutional and market incentives could help reach the levels of afforestation needed for achieving food and land system targets. This could include efficient land-clearing regulations to protect primary forests and forest regrowth (Marcos-Martinez et al. 2018; Simmons et al. 2018) and higher demand for land-based emission offsets.

The fact that other variables seem to have a marginal influence on target achievement (within the bounds of the analysis) does not mean they are unimportant. The analysis was set up as a stochastic “shock” experiment where variables changed independently within SSP narratives. However, if we were to define sets of cost-effective conditions to achieve sustainability targets, we might find different variable combinations not necessarily dominated by the robust variables identified here. Additionally, our work captures broad national-scale trends through aspatial modelling. System dynamics that primarily play out at local scales are out of the scope of this analysis. For example, improvements in crop production arising from better rotations would have multiple benefits that are not modelled here, such as reduced nitrogen application and leaching, improved soil organic carbon, improvements in the production of energy, protein and farm gross margins (Hochman et al. 2020), and reduced pesticide usage which could lead to reduced chemical toxicity (Navarro et al. 2021). However, the effect of these improvements will vary with local soil, landscape, and climatic conditions and hence would require high-resolution spatial modelling. These issues would have to be incorporated into national-level analyses from the bottom-up to maintain spatial accuracy. Yet, we have sought to strengthen our analysis using the best spatially explicit data and modelling available in the calibration of different sections of the Calculator (FABLE Consortium 2020; Marinoni et al. 2012; Marinoni and Navarro 2017; Navarro et al. 2016). Through this approach, we expect that national values are consistent with projections from aggregated results of the most detailed spatially explicit models.

The results also reveal Australian food security is influenced by import and export growth. Exports have been set to vary uniformly between 1.5 and 2 times the exports observed in 2010, and imports have been set to vary uniformly between 0.7 (30% reduction in imports) and 2 (doubling of imports). Such ranges are consistent with Australia’s current and foreseeable policy stance, which is in favour of growing agricultural exports (DAWE 2021). Ambitious export targets, however, increase the pressure on the land system and might compromise the ability of Australia to meet sustainability targets.

**Policy implications**

The Australian food and land system is a key driver of economic growth within the country and contributes to the food security of millions, particularly in the Asia-Pacific region and also to developed countries like the USA and UK. However, this system faces growing global and domestic issues (e.g. climate change, supply chain disruptions, changes in diets) (Shukla et al. 2019). The analysis suggests there are pathways towards greater sustainability and resilience in the Australian land-use sector, but the kinds of structural changes and interventions needed will require significant buy-in from key stakeholders about the need for systemic
change. This could help drive coordinated actions to maintain the local and global relevance of the Australian food and land system. Understanding the bounds within which this system needs to change and operate to achieve sustainability targets could enable greater clarity and flexibility during discussions between decision-makers and stakeholders.

Our analysis demonstrates the complementarity of scenario discovery with tools like the FABLE Calculator to exhaustively explore the various trade-offs and benefits of interventions in domestic food and land systems. This capability allows rapid exploration of the range of conditions needed to achieve country-level sustainability targets. Once regions of interest are identified, deep-dive analysis with more complex, spatially explicit models could be implemented to investigate the local impacts of interventions in the food and land system and design more resilient sustainability policies.

**Contributions and caveats**

Our work follows a string of studies aiming to apply scenario techniques to Integrated Assessment Models and addresses a common limitation where exploring a number of scenarios representative of the input parameter space is prohibitive due to the large computational requirements and the presence of deep uncertainty. This study shows an approach to increase the explanatory power of food and land system models like the FABLE Calculator, derive useful insights on how different aspects of food and land-use systems influence each other, and focus the search for resilient pathways to sustainable futures. This approach allows stakeholders to test the implications and drivers of a wide range of scenarios and to identify the main drivers of outcomes of interest and the direction of their impact. It also allows the investigation of synergies and trade-offs across targets and facilitates model development and debugging by highlighting conceptually inconsistent results.

Datasets generated during scenario discovery analysis could be used to train probabilistic or machine learning models to explore more quickly potential food and land system outcomes under a wider range of possible futures and find optimal or adaptive pathways almost in real time. While the current approach relies on proprietary software for the Monte Carlo simulation in Excel, it could be implemented in open-source modelling languages, e.g. using a combination of R scripts and VBA to control Excel via its Component Object Model interface.

The results of this analysis are dependent on the tuning of parameters to suit Australian conditions. The same analysis applied to a FABLE Calculator representing other countries’ conditions could reveal different dynamics and pressure points in their food and land-use system. For example, the results showed how crop productivity growth had a relatively small influence on the targets analysed here. Baseline crop yields in the Calculator were obtained from the most reliable sources and have been used over the years in numerous studies (Bryan et al. 2016; Gobbert et al. 2017; Hochman et al. 2016, 2020; Marinoni and Navarro 2017, 2018; Navarro et al. 2016). Analysing historical productivity trends in Australia (FABLE Consortium 2020) gives an estimated historical crop productivity growth at 0.75% p.a. (revenue weighted sum of broadacre and horticultural crops). In this analysis, the potential future crop productivity growth spans a wide search space between −0.5% p.a. and 1.25% p.a. Since Australia produces enough food to feed 51 million people worldwide (NFF 2017) (greater than twice the country’s population), it is not surprising that those potential realisations of productivity change have little effect on Australia’s food security. In reality, Australian crop productivity change will significantly affect global food security through increased or decreased agricultural exports. Other countries without such an oversized agricultural production engine will find national food security is more correlated with crop productivity growth. It is also important to note that using dietary energy intake to measure sustainable food intake is a simplification of a complex issue. The inclusion of a complete measure of nutrition covering other important macronutrients (e.g. protein, fibre, iron, zinc, vitamin A, vitamin B12) could reveal important links between crop productivity growth and domestic and global nutrition that are beyond the scope of this analysis. We also note that some Representative Concentration Pathways (RCP) can be linked to more than one SSP. For instance, Riahi et al. (2017) show that SSP2-RCP2.6 or SSP3-RCP4.5 is possible, while SSP3-RCP2.6 seems difficult. While we do not model other combinations of RCP with SSP, the impact of climate change in the Australian food and land-use system is estimated to be marginal by 2050. Such result is consistent with previous analysis based on multi-sector models and a partial-equilibrium model of Australian land use (Brinsmead et al. 2019; Gao et al. 2016).

**Conclusion**

Robust assessment of sustainable development pathways requires modelling of both the known (deterministic) dependencies between variables and general system dynamics, as well as stochastic relationships between human and environmental variables impacting system outcomes. Based on a model of the Australian food and land system and scenario discovery methods, we investigated multiple sets of conditions that could lead to achieving sustainability targets. Sustainability targets were defined around sustainable levels of food consumption,
afforestation, water use, emissions, biodiversity conservation, and exports. We simulated food and land system outcomes for a set of 200,000 scenarios linked to the narratives of shared socioeconomic pathways 1, 2, and 3. We found that around 10% of the SSP1 scenarios could achieve all modelled sustainability targets. However, practically none of the scenarios based on SSP2 and SSP3 conditions could achieve such targets.

Livestock productivity and density, afforestation, and diets were identified as critical variables to achieve sustainability targets. Policies, research and development, and investment in these areas could improve the likelihood of the Australian food and land-use system achieving a sustainable future. However, resilient sustainability strategies should consider solutions based on multiple food and land system components, rather than relying on a few variables to achieve desired outcomes. By exploring how drivers of food and land systems interact and influence outcomes over a comprehensive range of possible futures, we show that it is feasible to identify solutions and policies that could result in more resilient sustainability pathways.

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