Title: Knowledge co-production for identifying sustainability indicators and prioritising solutions for food and land system transformation in Australia.

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Abstract

The sustainable transformation of food and land systems requires the rapid implementation and scaling up of a broad suite of solutions to meet the Sustainable Development Goals (SDGs). Decision-making frameworks are needed to identify suitable indicators and prioritise solutions at national scales. Using a knowledge co-production framework, we convened 150 stakeholders from 100+ organisations to identify 18 nationally relevant indicators that aligned with critical SDGs describing a sustainable food and land system for Australia, in addition to 78 key solutions (supply- and demand-side) to enable progress against these indicators. We then asked subject matter experts to code the impact of each solution on each indicator using an adapted interaction mapping method accounting for uncertainty. The solution category 'Protecting and restoring nature', which included solutions targeting conservation and restoration, showed the highest potential for capturing synergies and avoiding trade-offs across multiple indicators. This category exhibited 34.6% of total major synergies, supporting the achievement of clean water and sanitation (SDG6), economic growth (SDG12), life under water (SDG14), and life on land (SDG15). The solution category 'Carbon sequestration', which included technological and biological carbon dioxide removal solutions, had the highest number of trade-offs with individual sustainability indicators (42.3%), particularly those relating to zero hunger (SDG2), wellbeing (SDG3), SDG6, SDG14 and SDG15. Our framework can be used to inform future research investment, support the prioritisation of solutions for quantitative modelling, and inform discussions with stakeholders and policymakers for transforming national-scale food and land systems in alignment with the SDGs.

Keywords

Sustainable Development Goals; synergies; trade-offs; regenerative agriculture; sustainable intensification; conservation

Introduction

Food and land systems are key to food security and well-being and are increasingly regarded as a key driver of environmental impacts and a major contributor to global environmental change (Hoek et al., 2021; Willett et al., 2019). Land-use change, biodiversity loss, freshwater use, atmospheric greenhouse gas (GHG) emissions, and nitrogen (N) and phosphorus (P) use have all surged due to agricultural expansion and intensification (Campbell et al., 2017; Foley et al., 2011; IPCC, 2019; Sukhdev, 2018). Global demand for agricultural goods is expected to increase further with population, income growth, and dietary shifts (Crist et al., 2017; FAO, 2018; Pereira et al., 2020; Willett et al., 2019). Recent studies therefore warn against the continuation of a business-as-usual trajectory of agricultural and land-use management, calling for a system transformation to ensure a sustainable trajectory for humanity (Clark et al., 2020; Fanzo, 2021; FOLU, 2019, 2021; Hebinck et al., 2021; Oliver et al., 2018; Rockström et al., 2020; Springmann et al., 2018; Steiner et al., 2020; Webb et al., 2020; Willett et al., 2019).

While a food and land system transformation has been defined and modelled at the global level (FOLU, 2019, 2021; Searchinger et al., 2018; Steiner et al., 2020; Willett et al., 2019), there is an urgent need to elaborate on what this would entail at the national level, particularly given the diverse starting points and roles of different countries and regions in a globalised agri-food system and to manage for the power dynamics and imbalances that exist within it (Allen & Wilson, 2008; Howard, 2021; Pereira et al., 2020; Steiner et al., 2020). The pathway towards food and land system transformation at the national level is not clearly defined (Béné, Prager, et al., 2019; Sukhdev et al., 2016), and there is a need for national scale frameworks to prioritise solutions that can deliver the best outcomes to meet United Nations Sustainable Development Goals (SDGs) (UN, 2015) that consider the complexity of the underpinning socio-ecological, socio-technical and political-economic systems (Fesenfeld et al., 2022; FOLU, 2021; Oliver et al., 2018; Pereira et al., 2020). Concurrently achieving all SDGs within the 2030 timeframe presents many challenges and requires managing the tensions between development, the environment, and the inherent trade-offs between SDGs (Bryan et al., 2019; Griggs et al., 2017; Orbons et al., 2024; Pradhan et al., 2017).

Progressing the global sustainability agenda requires successful national-scale implementation of solutions (Gao & Bryan, 2017). There are many competing narratives as to what constitutes a sustainable food and land system and what the optimal mix of solutions is for achieving a sustainable transformation (Béné, Oosterveer, et al., 2019; CSIRO, 2023; McRobert et al., 2022; Mosnier et al., 2022; NFF, 2019; Roe et al., 2021; Searchinger et al., 2018; Springmann et al., 2018). Several studies have highlighted the need to move beyond a focus on productivity or single-paradigm approaches (Allen & Wilson, 2008; Dornelles et al., 2022; Faulkner, 1944; Howard, 2023; Howard, 2021; Lindgren et al., 2018; Sukhdev, 2018), suggesting a shift to a systems approach in defining and measuring sustainability to account for regional variations at the national and sub-national scale (Fanzo et al., 2021; Hebinck et al., 2021). Global scale frameworks have been developed for establishing and monitoring progress towards indicators (e.g. Fanzo et al., 2021; Hebinck et al., 2021; Jones et al., 2016; Stefanovic et al., 2020; Willett et al., 2019), for supporting decision-making and the implementation of solutions for system transformation (Béné, Oosterveer, et al., 2019; Silva et al., 2022; TEEB, 2018). Australian-specific sustainability frameworks identifying indicators and roadmaps for sustainable food and agriculture system have been developed (CSIRO, 2023; McRobert et al., 2022), but lack focus on which solutions should be prioritised and their potential synergies and trade-offs, which are critical for supporting strong governance, decision-making and negotiations between stakeholders (Hebinck et al., 2021; Oliver et al., 2018).

The sustainable transformation of food and land systems requires the rapid implementation and scaling up of a broad suite of behaviour-oriented (demand-side) and technology-driven (supply-side) solutions as well as alternative paradigms such as agroecology (Béné, Oosterveer, et al., 2019; Gordon et al., 2023; Herrero et al., 2020; Röös et al., 2017; Wezel et al., 2009; Wezel et al., 2014; Wezel & Soldat, 2009). However, solution prioritisation depends heavily on indicators selected for assessing system sustainability (Garnett, 2014). The diverse views on choice and weighting of indicators diverge even more at regional and national scales (Bennett et al., 2021). To manage for this at the national and sub-national scale, to capture the local specificity of food and land systems, local contexts and stakeholders should guide the development of locally relevant indicators and solutions (Bandari et al., 2022; Béné, Oosterveer, et al., 2019; Moallemi et al., 2021; Moallemi et al., 2020; Szetey et al., 2021).

Frameworks are required to prioritise solutions and focus the development of integrated models for scenario analysis, to inform policy and highlight knowledge and technology gaps (Nilsson et al., 2018; Nilsson et al., 2016). However, to adequately capture the complexity of sustainable transformations and support effective adoption, frameworks must account for the diversity of stakeholders across the food and land system from land-use practitioners and civil society to national governments and private sector and navigate the competing dimensions of food and land system sustainability and the complex interdependencies (and trade-offs) between SDGs (Béné, Prager, et al., 2019; Oliver et al., 2018; Pereira et al., 2020).

System level transformations require transdisciplinary collaboration across a broad range of stakeholders. This enables more diverse views and values, minimises the risk of unforeseeable consequences and/or trade-offs, to more comprehensively reflect available knowledge and conceptualise novel sustainability innovations (Mauser et al., 2013; Moallemi et al., 2020; Nielsen et al., 2020; Pereira et al., 2020; Schneider et al., 2021). Iterative and collaborative processes that integrate knowledge and stakeholders from diverse domains are known as *co-production* or co-creation (Mauser et al., 2013; Reed et al., 2022; Wyborn et al., 2019) and result in context-specific knowledge which can be used to underpin the development of locally contextualised sustainability pathways (Chambers et al., 2021; Mauser et al., 2013; Norström et al., 2020). The value of co-produced knowledge is well established in the field of sustainability science (Jassanoff, 2004; Moallemi et al., 2021; Moallemi et al., 2020) leading to mutually reinforcing and reciprocal outcomes that represent more inclusive, legitimised, impactful, and systemic change for local contexts (Jassanoff, 2004; Norström et al., 2020; Schneider et al., 2021; Wyborn et al., 2019). As such, adopting co-production methods can improve the integration of environmental, social, economic, political and cultural factors into conceptualising system sustainability, and support navigating synergies and trade-offs in a just, transparent, and efficient manner (Béné, Prager, et al., 2019; Chambers et al., 2021; Moallemi et al., 2021; Moallemi et al., 2022).

In this study, we bring together a diverse range of stakeholders to co-produce an extensive suite of nationally relevant SDG-aligned sustainability indicators and solutions for the Australian food and land sector. We then apply an adapted interaction mapping method (Nilsson et al., 2016) to rapidly assess the relationship between nationally relevant solutions and indicators, and global SDGs. We demonstrate the value of this framework for identifying ‘win-win’ sustainability solutions that can progress multiple indicators and SDGs at the same time, and identify solutions with trade-offs (i.e., solution-indicator interactions with negative causal relationships) (Allen et al., 2019; Griggs et al., 2017; Hopkins et al., 2021). Our approach also identifies solutions with impacts that lack consensus and gaps in indicators and SDGs where few solutions are currently known or available for the local context, highlighting priorities for future research and investment. This study is a targeted contribution to the broader body of work required to enable the sustainable transformation of the Australian food and land system.

Methods

Study area: the Australian food and land system

Australia is a significant global food and fibre producer, particularly for key commodities such as beef, sheep and wool, dairy, wheat, wine, and cotton (DFAT, 2020) (Figure 1). The economic and social importance of agriculture is juxtaposed by its significant negative impacts on the environment, most notably on biodiversity, water availability and quality, and greenhouse gas emissions (Turner et al., 2018). Australian agriculture is export-oriented, with 72% of the total annual value of agricultural production going to exports. This accounted for 12% of goods and services exports and 1.9% of Australia's GDP in 2021. Agriculture currently accounts for 55% of Australian land use (excluding timber production), 74% of extracted water (ABARES, 2022; ABS, 2020-21), and 17.5% of GHG emissions (DCCEEW, 2023).

There are several sustainability narratives promoted for the future of Australian agriculture, which reflect elements of the global food system transformation (Béné, Oosterveer, et al., 2019; Grundy et al., 2016). These range from encouraging technologies and farming practices that can reduce resource use, GHG emissions and depletion of soils (Turner et al., 2016), stricter conservation and carbon sequestration priorities and funded initiatives (Bryan et al., 2014; Bryan, Runting, et al., 2016), and facilitating shifts towards sustainable diets and food waste reduction (Geyik et al., 2022; Springmann et al., 2018; Willett et al., 2019). At the same time, there are a number of potentially conflicting socio-economic priorities such as calls for continued growth in the value and volume of exports (NFF, 2019), concerns around food system resilience and nutrition security due to the rising costs of fresh produce (Ridoutt et al., 2017), and concerns around farmer welfare and vitality in regional areas (NFF, 2019).

Theory of change

Several narratives and pathways for the sustainable transformation of the Australian food and land system have been described (Béné, Oosterveer, et al., 2019; Bryan, Nolan, et al., 2016; CSIRO, 2023; Gao & Bryan, 2017; Grundy et al., 2016; NFF, 2019). Successful transformation requires buy-in from stakeholders across a system, achievable through a co-production methodology. We adopt the framing of Scoones et al. (2020) to conceptualise the system transformation required, shifting from its current unsustainable state to the desired state using the SDGs as the framework for achieving the sustainable transformation of the Australian food and land system. Our study makes a targeted contribution to this broader theory of change by improving our locally specific knowledge of solutions and sustainability indicators for the transformation of the Australian food and land system. Likewise, this approach builds our understanding of the solution-indicator relationships to guide decision making. We propose that the expected value of information (EVOI) of solution-indicator relationships derived from co-production processes, where the expected increase in the value of information is associated with obtaining more information relevant to the decision process (Dakins, 1999), can support a rapid and well-informed sustainability transformation for Australia.

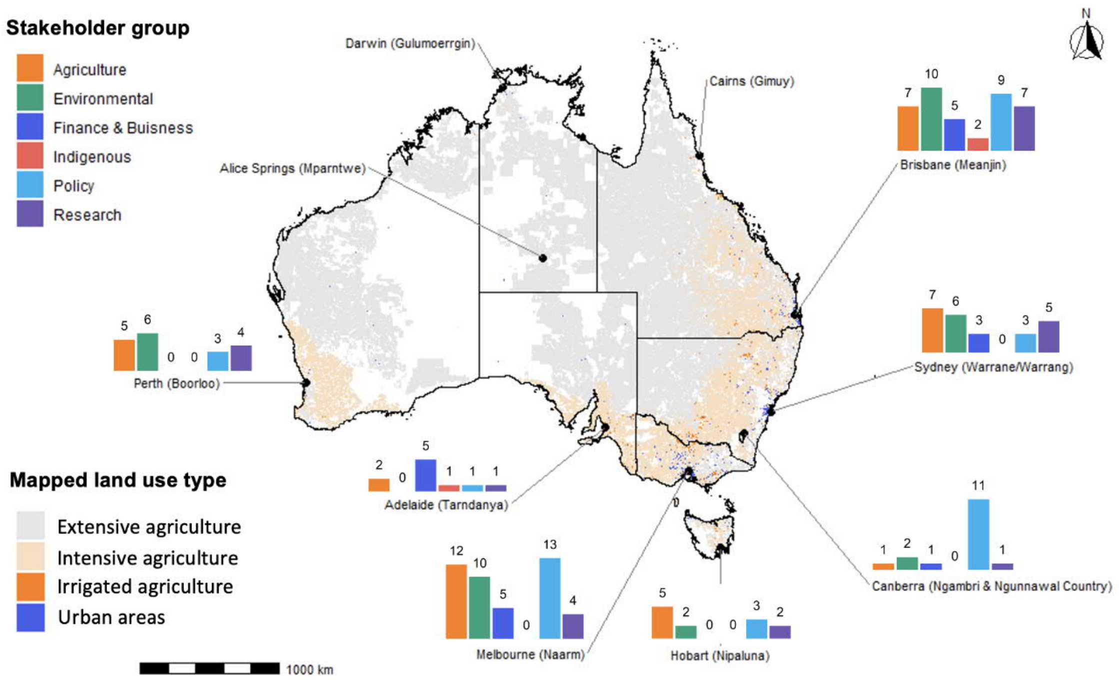

Figure 1. Agricultural land use map for Australia, displaying areas under extensive grazing, intensive grazing, cropping and horticulture as well as urban areas, with State and territory administrative boundaries overlayed. The bar graphs display the number of individuals involved in this project within each stakeholder groups for each major city co-production workshop. Land use data for Australia is taken from the Australian Land Use Map 2010. Stakeholder data was collected during workshops in Phase 1 of this study.

A knowledge co-production framework for identifying indicators and prioritising solutions

The knowledge co-production framework for identifying indicators and prioritising solutions applied in this study (Figure 2) is characterised by three distinct phases: Phase 1 development of an indicators and solutions database with stakeholders; Phase 2 refinement of the solutions and indicators database; and Phase 3 mapping of solutions-indicator interactions using an adapted interaction mapping method (Nilsson et al., 2016) to determine win-win solutions, trade-offs, and gaps in current availability of solutions to support the achievement of different indicators and SDGs.

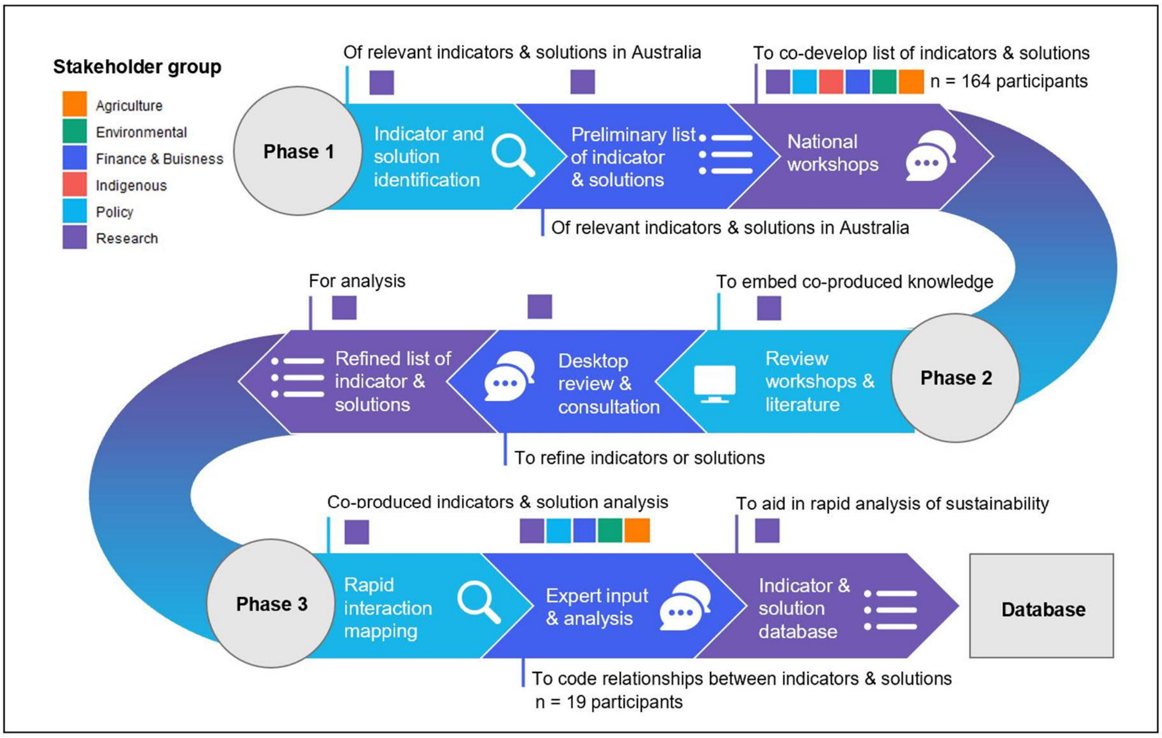

Figure 2. Visual representation of the process used to develop the knowledge co-production framework for identifying indicators and prioritising solutions. Coloured squares represent stakeholder engagement. Along the pathway light blue represents processes, deep blue represents inputs and purple represents outputs and goals. Icons are designed by Freepik from Flaticon. The number of participants engaged during national workshops (Phase 1) and expert analysis (Phase 3) are indicated (n=).

Phase 1: Developing a preliminary list of indicators and solutions.

We undertook a review of academic and grey literature to identify an extensive preliminary list of supply-side (i.e., practice change/technological) and demand-side (i.e., behaviour change) solutions, focusing on major reports by the Food and Land Use Coalition (FOLU) (2019), Project Drawdown (2019), World Resources Institute (2018); Beyond Zero Emissions (2014); and the EAT-Lancet Commission (2019). Candidate supply-side solutions included land use and management practices spanning sustainable intensification, agroecological, and conservation and circular economy paradigms, breakthrough technologies, alternative proteins, nature-based solutions, energy decarbonisation, and carbon sequestration. Candidate demand-side solutions included reducing food and fibre waste and loss and dietary shifts. Supply-side solutions included spanned the agricultural production stage as well as key upstream industries that supply goods and services to agricultural producers such as water, fertilisers, pesticides, animal feeds, and energy (electricity and fuel) (Gao & Bryan, 2017). Supply chain solutions, although critically important to the sustainable transformation of the food and land system (Ahumada & Villalobos, 2009; FAO, 2018; FOLU, 2021; Poore & Nemecek, 2018; Steiner et al., 2020) were outside the scope of this study.

A preliminary list of indicators was developed in parallel following the same approach to capture the diversity of economic, socio-cultural, and environmental criteria relevant to the Australian food and land system. These indicators drew on well-established international frameworks such as the Economics of Ecosystems and Biodiversity (TEEB) agri-food (2018), the System of Environmental Economic Accounting (SEEA) (2014) and FOLU (2019).

In 2019, we conducted a series of stakeholder engagement workshops convening 164 stakeholders from 100+ organisations over seven workshops in capital cities across Australia. Workshop participants included a mix of agricultural industry representatives, federal and state government, finance and investment, Aboriginal and/or Torres Strait Islander peoples, landowners, natural resource managers, research/advisory and development organisations, and sustainable agriculture consultants (Figure 1). We aimed for an even gender representation but did not request participants to self-identify gender during the participation process. Across all workshops, policy makers from state and federal government agencies made up 26.2% of participants, agricultural representatives and landholder 23.8%, environmental organisations and natural resource managers 21.9%, researchers 14.6%, finance and business 11.6%, and Aboriginal and/or Torres Strait Islander peoples 1.8% (Figure 1).

Workshop participants were presented with the preliminary solutions in the first session, and the preliminary indicators in the following session. In both sessions they were invited to review the lists independently and provide feedback using sticky notes against a feedback matrix capturing what they liked, wanted to add, wanted to remove, or had questions or comments about. Sticky notes were analysed using Nvivo13 (2020, R1) (Lumivero, 2020) to produce word clouds highlighting priority indicators and solutions as identified by stakeholders (Figure S1 Supplementary Information). We synthesised these workshop outputs to form a preliminary database of co-produced solutions and indicators (see Supplementary Information for further details on the co-production workshop process).

Phase 2: Refinement of indicators and solutions

We refined the solutions and indicators database using ad-hoc expert consultation and further literature reviews. The indicators were mapped to relevant SDGs and described (Table 1). Indicators were arranged under the SDGs Wedding Cake framework (Sukhdev & Rockström, 2016) as a way of conceptualising how healthy and sustainable food directly or indirectly connects all SDGs by encompassing the social, economic, and ecological aspects of the SDGs (Table 1). Drawing on established frameworks such as FOLU (2019) and outputs from the workshops, 19 high-level solution categories were established to enable grouping of like solutions for the Australian context (Table 2).

Each solution was mapped to the appropriate category from the FOLU '10 critical transitions' framework (FOLU, 2019). Adopting the FOLU framework cuts through ideological or paradigmatic approaches to land management and land use and enables solutions from across multiple paradigms to be included simultaneously in the database. For each solution, we finalised the framing in terms of actual land-use or practice change that can be modelled, for example, virtual fencing is not identified as a standalone solution - rather as an enabling technology for managing grazing pressure (a practice defined with a specific bundle of assumptions). Each solution was then allocated to a high-level solution category with similar solutions, for example Protect and restore nature (Table 2).

Phase 3: Mapping solution-indicator interactions and SDGs

To ensure alignment with global goals, the final list of selected indicators was mapped to 9 relevant SDGs: Zero hunger (SDG2); Good health and wellbeing (SDG3); Clean water and sanitation (SDG 6); Affordable and clean energy (SDG7); Decent work and economic growth (SDG8); Responsible consumption and production (SDG12) Climate change (SDG13); Life under water (SDG14); and Life on land (SDG15).

We then applied a team coding approach of an adapted interaction mapping method using a 7-point scale (Nilsson et al., 2016) to encode the strength and direction of each solution-indicator interaction (Figure 3). We defined a synergy as a positive causal relationship between a solution and indicator, with three levels of interaction, and a trade-off as a negative causal relationship between a solution and an indicator, with three levels of interactions (Allen et al., 2019; Hopkins et al., 2021; Nilsson et al., 2018). Levels of synergy and trade-off are defined in Figure 3 (Nilsson et al., 2018; Nilsson et al., 2016). To simplify the mapping process and to ensure consistency, coders were asked to focus on the direct co-benefits/trade-offs rather than the secondary or indirect co-benefits /trade-offs of each solution-indicator interaction. It was outside the scope of this research to consider the multiple non-linear, irreversible and cumulative processes that may exist between solution-indicator relationships.

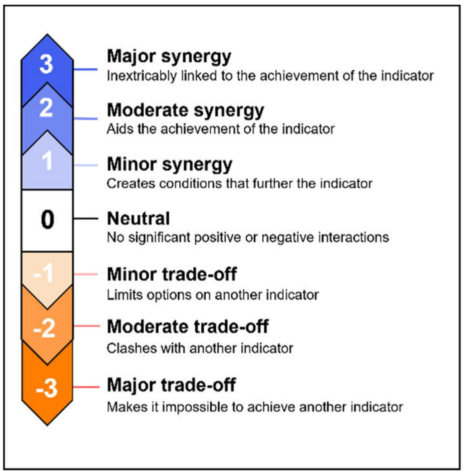

Figure 3. Rapid interaction mapping coding classes: adapted 7-point scale (Nilsson et al., 2016).

The relationship between a solution and each indicator is inherently complex. For example, the impact of solutions can vary by context (e.g., spatial location, scale and temporal dimensions), by the specific way in which the solution is designed and implemented, and by the people or organisations adopting these solutions. To manage for this complexity three teams of expert coders (herein referred to as coders), a subsection of stakeholders and researcher from Phase 1, coded every interaction between the 78 solution and 18 sustainability indicators. The first team was made up of a food system researcher and a conservation scientist, the second team was made up of two practitioners with expertise in climate and food systems and, the third team was a single practitioner with expertise in climate and food systems. Coding teams may have their own biases due to their knowledge base and expertise. To overcome these potential sources of uncertainty all coding teams initially reviewed the same sub-sample of solution-indicator interactions and intercoder reliability was assessed using the Fleiss' Kappa statistic (Fleiss, 1971) through the *raters* package in R (Quatto & Ripamonti, 2022; Team, 2020). Disagreements were discussed to reach an agreement across all sub-sample solution-indicator interactions prior to progressing to screening all interactions. We aimed for agreement as the intent of the study was to enable the use of the rapid coding method to prioritise solutions based on a consensus relationship between solutions and indicators.

For each solution-indicator interaction an average rating was determined. Results were interrogated by individual solution, solution category, indicator and by SDG to determine the likely performance of a solution in achieving a sustainable transformation of the Australian food and land system that aligns with global goals (Supplementary Information 3). To represent empirical uncertainty at a solution-indicator level, for each solution-indicator interaction, we calculated the difference between the maximum and minimum level assignment on the 7-point scale (Figure 3) across the three coders. The average level of (dis)agreement between coders is expressed as the difference in levels (e.g., 0, 1, 2 and 3 levels) between coders on the strength and direction of the solution-indicator interaction. Strong consensus was defined as between 0 and 1 levels of (dis)agreement between coders, weak consensus was defined as between 3 and 4 levels of (dis)agreement between coders. For relationships where coding teams greatly disagreed (by a level of 3 or 4, for example neutral vs. major synergy), expert input was gained to reach a consensus on the solution-indicator interactions to add additional layer of rigour to the interaction codes (Hill et al., 2005; Hill et al., 1997). We sought expert input through a multidisciplinary team of 13 scientists with expertise across environmental science, climate, food and agricultural systems, ecosystem and forest science, public health and nutrition, systems modelling, energy, and sustainability who provided additional ratings for solution-indicator relationships with weak consensus.

Results

Co-production and mapping of the solutions and indicator database

Phase 1 (database development) workshop series resulted in: a total of 496 comments on solutions and 478 comments on indicators (add, modify, remove, like); 86 substantive comments on wording of or gaps in preliminary solutions were considered; 375 comments and questions on indicators; 24 wording changes to existing solutions suggested; and 7 new solutions (Figure 4). Phase 2, refinement of the framework, resulted in 18 co-produced sustainability indicators that mapped to 9 SDG domains (Table 1), and 78 co-produced sustainability solutions categorised into 19 broader solution categories and mapped to the FOLU ‘critical transition’ categories (FOLU, 2019) to support the sustainable transformation of the Australian food and land system (Table 2). Supplementary Information 1 provides detailed descriptions, examples, and references for each solution.

Figure 4. Workshop participants co-producing the solutions and indicators database: A) Participants in Sydney, 9th April 2019; B) Participants in Canberra, 10th April 2019; C) Participants in Melbourne, 26th March 2019; D) Participants in Hobart, 8th May 2019; E) Participants in Brisbane, 4th April 2019.

In Phase 3 (mapping solution-indicator interactions), a total of 1440 solution-indicator interaction pairs were mapped. Across all solutions-indicators assessed a Fleiss' Kappa value of 0.6 indicated 'moderate' inter-rater agreement. This level of agreement was deemed acceptable due to the complexity of the mapping process (Cohen, 1960; Fleiss & Cohen, 1973; McHugh, 2012). There were nine solution-indicator interactions where strong disagreement occurred between coding teams (difference of 4 levels) and 57 solution-indicator interactions where disagreement occurred (difference of 3 levels). Detailed results for the Kappa analysis are located in Supplementary Information 2.

Here we focus on results from Phase 3, summarised by solution category to explore locally relevant solutions to meet (or hinder) the achievement of sustainability indicators nationally, and more broadly contribute to global SDGs (Figure 5). We highlight solution categories with strong consensus between coders (between 0 and 1 levels of (dis)agreement) and those that show most promise for achieving multiple indicators. Key trade-offs and gaps that require consideration to meet sustainability goals will be highlighted. Figure 5 provides a summary of the spread of synergies and trade-offs for solutions across indicators, mapped to SDGs. Of the total solutions identified, 39.7% were found to have major synergies with the achievement of SDGs, and 16.7% to have associated trade-offs. See Supplementary Information 2: Extended results for detailed results for all synergies and trade-offs.

Priority 'win-win' solutions

The solution categories 'Protecting and restoring nature', 'Circular economy and energy decarbonisation' and 'Increased crop productivity' displayed synergies across diverse sustainability indicators. These solution categories cumulatively represented 59.6% of major synergies and 30.2% of moderate synergies, across 10 and 15 indicators, respectively. In total, 'Increased crop productivity' had the greatest number of synergies (minor, moderate and major) across indicators, representing 10.9% of total coded synergies. 'Increased crop productivity' also had the highest number of minor synergies (11.4%) between 8 solutions and 16 indicators mapping to 7 SDGs, however coders had strong disagreement over these interactions. This solution category was also found to create the conditions to deliver the highest number of socio-economic and health co-benefits (Table 3).

The solution category 'Protecting and restoring nature' had the highest number of major synergies (34.6%, Table 3) towards achieving 7 sustainability indicators mapping to SDG6, SDG12, SDG14, and SDG15, with strong consensus between coders. Within this solution category, SDG15 and SDG6 had the highest number of individual solutions coded as major synergies, with 50.0% and 27.8% of solutions respectively. These solutions included conservation and restoration activities such as expanding protected areas and improving their management and connectivity, minimising runoff, fire risk management, wetland conservation and the rehabilitation of floodplains, waterways, and riparian areas. Interestingly, no major synergies and only 18.8% of total synergies for this solution category were linked to the achievement of SDG13.

The solution category 'Circular economy and energy decarbonisation' had the second highest number of major synergies (17.3%, Table 3) towards achieving 5 indicators mapping to SDG7, SDG12 and SDG13, with strong consensus between coders. These solutions were on-farm practice changes that would see shifts in fertiliser and feedstock requirements and energy production and use. A higher number of moderate and minor synergies were coded for this solution category: 28.9% of total synergies were moderate with over half of these moderate synergies aiding the achievement of SDG12; and 57.9% of total synergies were minor synergies creating the conditions for achieving all 9 SDGs. Proportionally, more minor synergies creating the conditions for the achievement of SDG8 and SDG12 were identified, suggesting economic and resource use efficiency co-benefits associated with this solution category. Only 1 solution-indicator interaction (on-farm energy efficiency) for this solution category was found to contribute towards the achievement of human and ecosystem health.

Key trade-offs

There were 13 solutions in total that worked in both synergy and trade-off with various sustainability indicators. Only 1.9% of all solution-indicator interactions were identified as trade-offs limiting options on another indictor, with 76.9% of total trade-offs limiting the achievement of SDG15, SDG6 and SDG8 (Table 4). Within these SDGs, indicators ‘Biodiversity’, ‘Soil’, ‘Water sustainability’, ‘Water efficiency’ and ‘Regional development’ cumulatively accounted for 69.2% of total trade-offs. Only 1 moderate trade-off was identified (Table 3): ‘Shifting to monogastric production’ clashed with the achievement of the ‘Animal welfare’ indicator, however this solution was also coded with major synergies for achieving emission reductions and moderate synergies with the efficient use of natural resources and improving productivity.

Despite major synergies for reducing carbon emissions and improving soil health, the solution category ‘Carbon sequestration’ had the highest number (44.0% of total, Table 3) of minor trade-offs. Solutions for bioenergy feedstock production, carbon plantations and carbon capture and storage were perceived to limit the achievement of human and ecosystem health and sustainability indicators. The solution ‘Bioenergy carbon capture and storage (BECCS)’ exhibited the greatest number of minor trade-offs (24.0%) limiting the achievement of human and ecosystem health and sustainability indicators. No trade-offs were coded for SDG6 and SDG7 (Table 4), and no major trade-offs were identified among solution-indicator interactions (impossible to achieve other indicators) (Table 3).

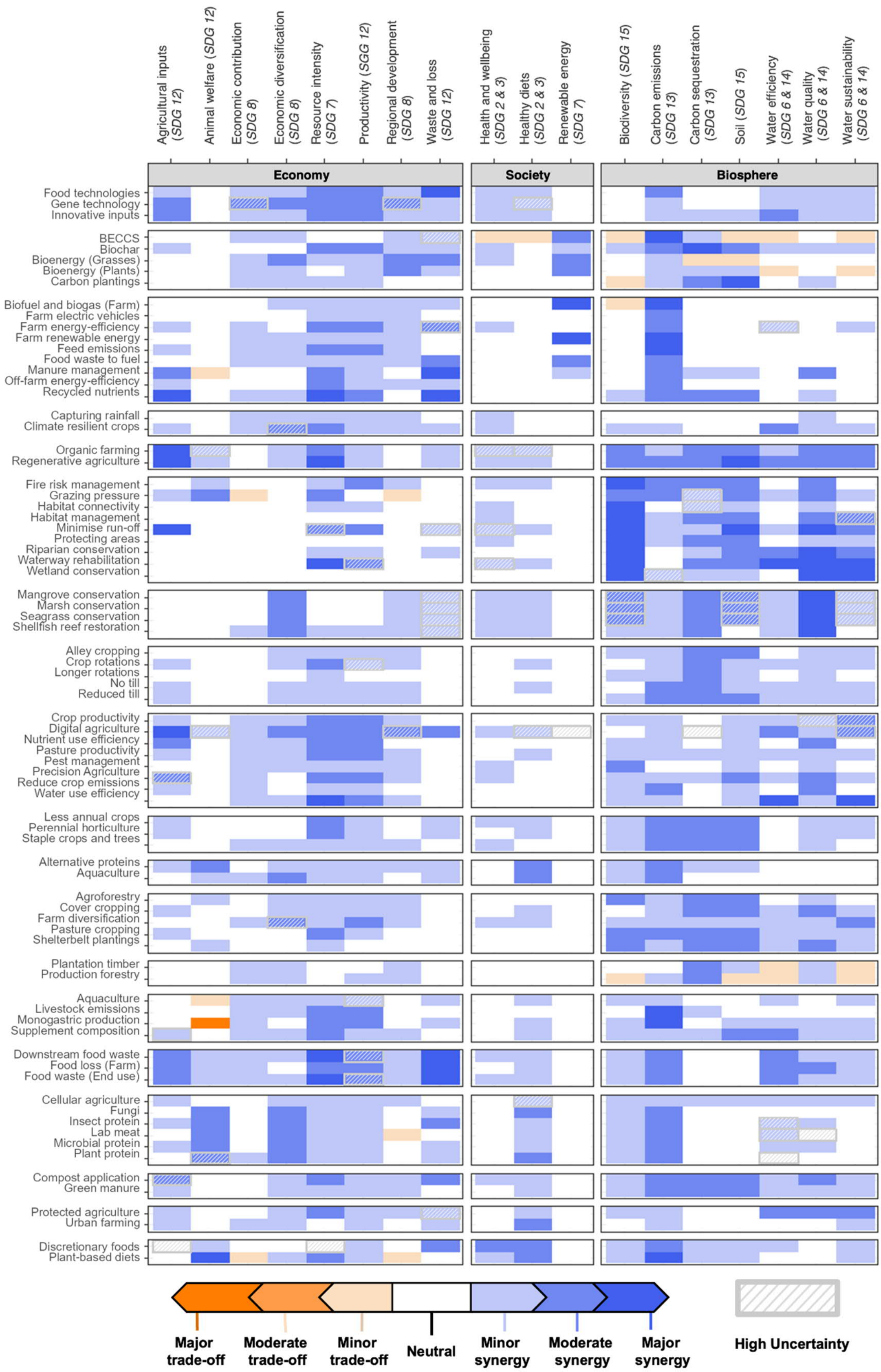

Figure 5. Interaction matrix for 78 solutions (left side column, individual solutions; right side column solution categories) and 18 individual indicators mapped to 9 SDGs and the 3 SDG

wedding cake categories: society, economy, biosphere (top row). Each solution-indicator interaction is assessed using the adapted 7-point scale (Nilsson et al. 2016) (bottom row) by the degree to which each solution-indicator interaction achieves each indicator/SDG (rows) and is likely to affect the achievement of other SDGs (columns). The colours represent the 7-point scale (bottom row), from major trade-off (darkest orange) to neutral (white) to major synergy (darkest blue); i.e. the darkest row/column intersections are those with the strongest influence (either positive or negative) for achieving an indicator/SDG (column label). Solution-indicator interactions that were assessed as having 3 levels of uncertainty are highlighted in a hatched pattern.

Identifying indicators and SDGs with limited solutions with major synergies

The indicator ‘Renewable energy’ was coded with <1% of total synergies and <1% of synergies across all levels of interaction. Very few major synergies were coded for achieving indicators ‘Carbon sequestration’, ‘Animal welfare’, ‘Water efficiency’, and ‘Soil health’. No solutions were coded with major synergies for the achievement of SDG2, SDG3 and SDG8. Table 4 provides a summary of the spread of synergies and trade-offs across SDGs to demonstrate coverage and gaps. These gaps and under-representation in delivering indicators and SDGs need careful consideration - they may be a product of methodological limitations or may highlight key challenges within the system or opportunities for innovation.

Discussion

We have developed a framework that draws on a diverse group of stakeholders and transdisciplinary experts to identify the strength and directionality of relationships across an extensive suite of solutions and locally-relevant national-scale indicators. Through this co-production process ‘Protecting and restoring nature’, ‘Circular economy and energy decarbonisation’ and ‘Increase crop productivity’ emerged as priority ‘win-win’ solution categories with the highest potential for capturing synergies and avoiding trade-offs. The solution category ‘Carbon sequestration’ emerged with the highest number of trade-offs for the achievement of human and ecosystem health and sustainability indicators and gaps were identified for achieving ‘Renewable energy’, ‘Carbon sequestration’, ‘Animal welfare’, ‘Water efficiency’, and ‘Soil health’ sustainability indicators. These findings and their likely implications are discussed below.

Solutions and indicators for food and land system sustainability

To maximise synergies across multiple indicators, we found that solution categories 'Protecting and restoring nature', 'Circular economy and energy decarbonisation' and 'Increase crop productivity' hold the greatest number of individuals solutions (with strong consensus) inextricably linked to meeting the greatest number of indicators at the national scale, and for achieving multiple SDGs. We considered these as 'win-win' solutions with very few co-occurring minor trade-offs and suggest prioritising these solution types for inclusion in future modelling efforts will support the identification of robust pathways towards a sustainable Australian food and land use system. We suggest that the greatest opportunity for innovation lies in the gap identified in the current set of solutions for achieving SDG7 at a national level. Identifying and/or developing new solutions to meet this gap could be considered a priority for future research to support Australia in achieving these SDGs.

Solution-indicator interactions are complex (Bandari et al., 2022; Griggs et al., 2017; Grundy et al., 2016; Nilsson et al., 2018; Nilsson et al., 2016; Pradhan et al., 2017; van Soest et al., 2019), thus we suggest that solutions or solution categories with conflict between major synergies and trade-offs such as 'Carbon sequestration', 'Shifting towards healthy and sustainable diets', 'Novel sources of protein' and 'Livestock productivity' are also important to feature in future work as they provide the greatest insights into the key sustainability challenges (Hebinck et al., 2021; Zurek et al., 2021). Quantifying the impacts of priority solutions where conflict between synergies and trade-offs occur will provide critical insights into the magnitude of effect across various SDG domain. Quantifying and modelling these impacts will enable us to explore challenging questions such as 'do the carbon sequestration benefits of a solution outweigh the biodiversity impacts', or 'how comfortable are we (as a society) to increase livestock productivity with certain solutions that compromise on animal welfare'. The achievement of so-called 'win-win' solutions will be enabled or accompanied by difficult societal choices or trade-offs (necessary burden shifting), and this must be clearly communicated (Béné, Oosterveer, et al., 2019).

Harnessing synergies and overcoming trade-offs and gaps

Identifying priority solutions is not as simple as identifying major synergies. Our results draw attention to the paradigmatic dichotomy of producing less or producing better (Gerber et al., 2013; Steinfeld & Gerber, 2010), and the importance of looking beyond the scope of a single indicator to evaluate a solution. Our results suggest that despite the broad range of important co-benefits to people and ecosystems derived from 'Protecting and restoring nature' solutions (Keith et al., 2021; Miralles-Wilhelm, 2021; Seddon et al., 2020), these solutions were not viewed by experts as major contributors at scale to the achievement of climate change mitigation for the Australian food and land system, and should not be viewed as a substitute for the rapid decarbonisation of the entire economy (Seddon et al., 2021). As such, priority solutions must also be contextualised by the sustainability goals co-produced by stakeholders (Bandari et al., 2022; Moallemi et al., 2021; Szetey et al., 2021) and informed by the intended scale of application (Gao & Bryan, 2017; Nilsson et al., 2016).

Triggering and accelerating change across the food and land system requires identifying points in the system where targeted solutions can enable positive feedback loops and activate positive tipping points (Fesenfeld et al., 2022; FOLU, 2021; Pereira et al., 2020). FOLU (2021) proposed a framework for identifying early signs of positive tipping points and suggest solutions and sequencing that hold the greatest potential for triggering these positive feedback loops. Like FOLU (2021), our results indicate that the solution category 'Protecting and restoring nature' holds many solutions that may underpin the transformation required. We suggest that our rapid approach to identifying 'win-win' solutions (and trade-offs) supports early identification of solutions that may trigger such positive tipping points. Sukhdev and Rockström (2016) demonstrated the hierarchy of SDGs for the food system, arguing that solutions that support conserving the biosphere (SDGs 6, 13, 14 and 15) underpin the success of achieving all other SDGs. As such, prioritising solution categories 'Conserving land' (8 solutions) and 'Conserving oceans' (4 solutions), solutions with multiple synergistic solution-indicator relationships and no identified trade-offs across biosphere SDGs (Figure 5), may support the sustainability transformation required for Australia.

Each solution is subject to complicated power relationships, temporal dimensions, multiple cascading effects and/or feedbacks and requires different options for institutional and societal innovation (Fesenfeld et al., 2022; FOLU, 2019, 2021; Howard, 2021; Pereira et al., 2020; Steiner et al., 2020). FOLU (2019) identified key actor groups and their roles in the transformation of the food and land system: government, business, farmers, investors, financial institutions, participants in multilateral processes and multi-stakeholder partnerships, and civil society. There are underlying actions required by these specific actors to enable transformations across different solution domains with many complex interacting relationships. For example, solutions in the 'critical transition' domain 'protect and restore nature' require government to establish and enforce policy, regulation, and incentive schemes while business and suppliers must establish transparent supply chains to enable these solutions to be realised successfully. Whereas solutions in the 'critical transition' domain 'scale productive and regenerative agriculture' require government and business to establish and scale payments for ecosystem services and improve training and access to technologies. Likewise, business and investors should invest in sustainable supply chains and deploy innovation financing (FOLU, 2019, 2021). While land managers and farmers are responsible for the implementation of many of the solutions identified in this study, the pace and scale of uptake and implementation will be largely determined by national and local policy, regulation, financing, and consumer demand. The role of each actor group in enabling these key transformations should be the focus of future research.

Highly optimistic global pathways often entail several assumptions (e.g., BECCS, afforestation) that may be at odds with the local sustainability context (Stoy et al., 2018). Without careful consideration and prioritisation of research and actions to attend these trade-offs, or without systematic oversight across the complexity of solution-indicator interactions, we run the risk of encountering unintended or unanticipated consequences of implementing solutions (Zurek et al., 2021) to achieve myopic or singular indicators. Our analysis identified key trade-offs for solution category 'Carbon sequestration' across multiple indicators and SDGs, indicating that solutions identified within these categories may have several risks and/or limitations, and require further exploration and deliberation with key stakeholders across sectors before they are considered for modelling and implementation. The solution 'BECCS', a Carbon Dioxide Removal (CDR) technology, had the highest number of trade-offs, spread across several indicators. Studies have quantified these trade-offs demonstrating that although BECCS provides the opportunity for ambitious levels of carbon sequestration there are risks to ecosystem services, threats to biodiversity and social and economic implications of displaced food production (e.g. Cobo et al., 2022; Stoy et al., 2018; Withey et al., 2019) which are highly context and site specific (Donnison et al., 2020). Compared to other studies (De Neve & Sachs, 2020; Ioannou et al., 2023; Mainali et al., 2018; Nilsson et al., 2016; Pradhan et al., 2017; Stoy et al., 2018), few trade-offs were identified. However, majority of these studies focused on synergies and trade-offs between SDG pairs rather than solutions to achieve them. Exploring Exploring this space for a suite of land management and land use practice solutions against SDGs revealed fewer trade-offs for the Australian context, however due to the qualitative nature of this study the magnitude of these trade-offs remains to be determined which will play an integral role in decisions making and policy agenda setting.

The greatest challenges and opportunities for the Australian context lie in the gap identified for achieving the ‘Renewable energy’ indicator. Many on-farm renewable energy opportunities exist, however policy and funding schemes are required to support and enable innovation in this space (Chel & Kaushik, 2011), likewise for the transition to renewable energy across the food and land sector for Australia (NFF, 2019). Limited infrastructure in rural areas is a barrier to the adoption of renewable energy and electrification solutions (e.g. Karakaya & Sriwannawit, 2015). This finding may also reflect the exclusion of transportation and refrigeration of goods/products (i.e. supply chain solutions from farm to fork) from the scope of this study, where further opportunities for decarbonisation exist through the adoption of renewable energy solutions (AEC, 2022) . It has been estimated that food system is responsible for ~18 Gt CO_2e/yr, amounting to 34% of global anthropogenic GHG emissions. On average, 71% (55-77%) of emissions in the food system come from agricultural production, suggesting that significant efforts are required in this domain (Crippa et al., 2021). However, solutions to reduce supply chain inefficiencies also offer great opportunity for decarbonisation and should be considered in future studies as they can make an important contribution to delivering system transformation (Poore & Nemecek, 2018; Steiner et al., 2020). Very few solutions were identified that are inextricably linked to the achievement of SDG2, SDG3 and SDG8. Achieving these SDGs with the current set of identified solutions for the Australian food and land system occurs primarily as a co-benefit. This is likely the product of solutions focusing on land use and practice change at the national scale, presenting an opportunity for innovation to include solutions that directly improve human health and wellbeing and regional livelihoods.

The intrinsic value of knowledge co-production for the food and land system

The complexity and uncertainty of transformation can be further intensified by adopting disciplinary silo approaches for designing pathways based on formalised methodologies that are less sensitive to cultural values, human preferences, and social complexities. Designing pathways for the food and land system requires transdisciplinary approaches that bridge scientific findings with stakeholder knowledge of local contexts and enable knowledge co-production. Given the large complexity and non-linearity in the dynamics of the food and land system and interaction with other systems, it is not possible to forecast the entire suite of potentially transformative sustainability solutions required to achieve the SDGs (Tàbara et al., 2018). The co-production frameworks such as the one presented in this study serve as a foundational tool for embedding knowledge from stakeholders from across a system in establishing indicators to measure sustainability and uncovering solutions to achieve them (Moallemi et al., 2021).

Sustainability goals that are prioritised in a co-creative process draw on the plurality of different visions for the future, local specificalities, and cultural narratives that various stakeholders present (Chabay et al., 2021; Jasanoff & Kim, 2015; Szetey et al., 2021). Likewise, a set of solutions for achieving goals needs to be co-developed. Stakeholders will more likely support planned solutions if there is a perceived a link to their social identities (Chabay et al., 2021) and reflects local knowledge (Manzo & Perkins, 2006). Constructive dialogues with diverse stakeholder groups about solutions can help in a just, equitable and publicly supported implementations that are widely supported (Chabay et al., 2021). Stakeholders can understand the surrounding cultural and political context and define what 'critical' solutions will be convincing and actionable on the ground.

Our framework is an attempt to provide a structured, systematic and meaningful approach identifying locally relevant indicators and solutions to enable locally-specific and system appropriate modelling that explores national scale contributions to global SDGs. To this end, this framework could be used by a broad range of stakeholders seeking to establish the greatest opportunities for climate change mitigation and simultaneously meeting environmental and socio-economic goals, and identifying the key trade-offs and gaps that must be navigated. We suggest that this framework is a useful, transdisciplinary tool that can be successfully applied at the national and sub-national level for identifying and prioritising key solutions to achieve locally relevant and contextualised solutions for sustainable transformation of the food and land use system.

Limitations and future research

We identify three key limitations. The first is methodological, where the co-production (Phase 1) of the solutions and indicators database are subject to participant bias. Despite best efforts for representation across sectors and management of power dynamics between different actor types (Bandari et al., 2022; Moallemi et al., 2021; Szetey et al., 2021), we cannot be certain that an even representation of stakeholders and opinions was achieved during Phase 1. Barriers and challenges to knowledge inclusion, exchange and transmission may have created some biases in our results (Schiller-Merkens & Machin, 2023). During Phase 3, the coding of synergies and trade-offs was undertaken by a small subset of stakeholders and researchers, as such it is limited in its representation of the diverse perspectives and knowledge of the large number of participants and stakeholder types involved in the co-production process in Phase 1. Likewise, bias and varying degrees of confidence in the encoding of synergies and trade-offs (Bandari et al., 2022), lack of research or content knowledge for some solution-indicator areas, and varied hypotheses between coders in terms of their assumed strengths in solution-indicator interactions or indirect impacts (Phase 3) also had an impact on the results. At the individual solution level, some solutions were grouped together to reduce the number of coded relationships. For example, the solution 'Regenerative agriculture' was used in this study to describe multiple practices that underpin a regenerative or agroecological approach to land management. This reductionist method results in the nuances of various land management practices that can be applied within the regenerative approach being overlooked, and the co-benefits potentially being under- or over-estimated by coders.

The second limitation is absence of quantified impacts associated with each solution-indicator interaction. This limitation constrains the use of the framework to prioritisation of solutions rather than implementation, as the magnitude of impact (both positive and negative) and feasibility of implementing solutions or achieving against an indicator remain unknown. In contrast, the absence of these details ensures a rapid and low-cost approach for prioritising solutions for future modelling exercises. Quantitative modelling of impacts (or technical potential) often entails a significant level of abstraction and is usually only possible for a subset of the total number of solutions considered in qualitative narratives. It is important for the qualitative mapping process to encompass all solutions. Although it is likely (but not certain) that experts would have implicitly incorporated feasibility considerations during the coding process, we suggest that additional screening is required based on an appropriate feasibility framework (e.g., Brutschin et al., 2021; Nielsen et al., 2020) to account for the technological, economic, behavioural, cultural, and social feasibility be modelled for the Australian context and to determine the availability of quality data. Despite these limitations we have developed a framework that allows for the successful integration of stakeholder co-produced and transdisciplinary expert knowledge to identify the strength and directionality of relationships across an extensive suite of solutions and indicators which would otherwise be unachievable through quantitative modelling.

The third is the absence of any consideration of temporal dimensions (and feedbacks) associated with each solution. We did not explicitly consider the multiple non-linear, irreversible and cumulative processes which could be used to support the identification of conditions for positive tipping points (Fazey et al., 2018; Fesenfeld et al., 2022; FOLU, 2021; Pahl-Wostl, 2009; Tàbara et al., 2018). It could be suggested that 'win-win' solutions with no identified trade-offs may in fact enable the conditions for positive tipping points to occur and should be considered for further research in exploratory modelling exercises. One such example is the solution 'Regenerative Agriculture', a bundle of solutions that exist within an alternative paradigm of socio-ecological dynamics, has been recognised by some for their transformative potential for food production and ecosystem repair (Gordon et al., 2023; Massy, 2013).

Future work could include the translation of the co-produced indicators into specific measurable targets that would enable monitoring progress towards the co-produced indicators of a sustainable food and land system for Australia. The next phase of research should bring together the same diversity of stakeholders to undertake a participatory visioning and backcasting process, underpinned by the indicators and solutions database, to explore possible pathways for achieving a single desired future for the Australian food and land system and articulating the steps required to realise the desired future (Bibri & Krogstie, 2019; Ebolor, 2023; Kanter et al., 2016; Quist & Vergragt, 2006). This should include examining the key drivers and mechanisms for transformative change, the risks, uncertainties and alternative pathways to achieving transformation (Fazey et al., 2018), and illuminate opportunities to harness positive feedbacks and balance negative feedbacks (Fesenfeld et al., 2022). The insights gained during this process could be analysed using the quantitative modelling tools underpinned by the research presented here to support stakeholder discussions and provide tools for decision and policy makers. This would successfully situate the findings of this targeted research in a broader co-production process that mobilises local knowledge from multi-level interactions to inform system transformation (Pahl-Wostl, 2009).

Policy insights

The sustainable transformation of the Australian food and land system requires appropriate governance, policy and market mechanisms and sufficient investment and funding to ensure the pace and scale of change required is achieved to meet SDGs within the 2030 timeframe. Rapid transformation can only occur if we recognise the interlinkages across different systems. Each system is inherently complex and interrelated with much political debate surrounding the need and approach. As such, any system transformation must be underpinned by early and systematic interventions that promote synergies while minimising trade-offs and spill overs across different economic sectors and systems (Moallemi et al., 2020; Soergel et al., 2021).

While this work is intended to prioritise solutions for data assembly and model development, qualitative insights can be gained by policy and decision makers. For example, policies that incentivise sequestration must account for the potential trade-offs with food and water security, energy, soil health, biodiversity, and socio-economic impacts to communities (CCA, 2023; Stoy et al., 2018). Likewise, our framework could support the rapid identification of positive tipping points for the sustainable transformation of food and land systems (Fesenfeld et al., 2022; FOLU, 2021; Steiner et al., 2020), and also provide the foundation for targeted research contextualised by local knowledge and advancing policy based on best practice science.

Conclusion

Co-production frameworks such as the one presented in this paper can be a first but important step towards engaging stakeholders in thinking and planning for sustainable food and land systems. Co-produced knowledge is also a critical early step in ensuring pathways for transformation are positioned for successful adoption among stakeholders. This study has provided a systematic overview of the likely synergies and trade-offs across a carefully selected suite of sustainability solutions for achieving national-scale sustainability indicators specific to the Australian food and land system that can scale to meet SDGs. It has advanced our understanding of likely ‘win-win’ solutions, identifying ‘Protecting and restoring nature’, ‘Circular economy and energy decarbonisation’ and ‘Increase crop productivity’ as priority solution categories for capturing synergies and minimising trade-offs. Likewise, it has highlighted some key gaps and trade-offs that exist in meeting sustainability indicators for the Australian food and land system. The solution category ‘Carbon sequestration’ emerged with the highest number of minor trade-offs with individual sustainability indictors ‘Water efficiency’, ‘Water sustainability’, ‘Biodiversity’, and ‘Soil health’, and a key gap was identified in solutions available for achieving the indicator ‘Renewable energy’. Our findings can directly inform data assembly and quantitative modelling for sustainable food and land systems for the Australian context and facilitate future stakeholder and stakeholder dialogues by transparently reporting on key trade-offs, gaps, and 'win-win’ solutions.

Acknowledgements

This research was conducted as part of the Climateworks Centres' Land use Futures program. We acknowledge and pay our respects to the Traditional Owners of the land on which this research was conducted across Australia. Special thanks to Amandine Denis-Ryan and Emily Byrne for their contributions to the solutions database and workshop development and Trish Cave for her contributions to the design and development of the workshops. Thanks to Javier Navarro Garcia (CSIRO, Agriculture and Food, Brisbane, Australia) for his contributions to the broader Land Use Futures program on various sustainability solutions and interventions. Thanks to K. Brunt and L. Knudsen for their data analysis contribution.

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Table 1. Co-produced solutions database. Solutions are grouped by solution category and are also mapped to FOLU critical transitions (FOLU, 2019).

Category	FOLU critical transition	Solution
Boost fibre production	Scaling productive and regenerative agriculture	Production forestry (timber, high-value timber)
	Scaling productive and regenerative agriculture	Increase use of plantation timber in buildings and materials (demand shift)
Breakthrough technologies	Harnessing the digital revolution	Food processing and safety technologies to reduce food loss and waste
	Scaling productive and regenerative agriculture	Gene technology
	Scaling productive and regenerative agriculture	Innovative agricultural inputs, (e.g. botanicals, enhanced efficiency fertilizers, holobiomics, macrobials, micro-irrigation/fertigation, microbials, nanoenhancers, nanofertilizers, nanopesticides, soil additives)
Carbon sequestration	Scaling productive and regenerative agriculture	Biochar
	Scaling productive and regenerative agriculture	Bioenergy from perennial grasses and coppiced woody plants for feedstock (including BECCS)
	Scaling productive and regenerative agriculture	Bioenergy from crop residue (non-BECCS)
	Scaling productive and regenerative agriculture	Bioenergy from woody perennials (non-BECCS)
	Scaling productive and regenerative agriculture	Carbon plantings (monoculture species)
Circular economy & energy decarbonisation	Building local loops and linkages	On farm biofuel and/or biogas production/use
	Building local loops and linkages	Food waste to fuel
	Building local loops and linkages	Improve manure management (compost and bioenergy) in intensive systems (e.g. dairy; pigs and poultry)
	Building local loops and linkages	Recycled organic nutrients from urban waste streams (compost from green waste; bio-solids)
	Building local loops and linkages	Renewable energy generation (and storage) on farm for electricity.
	Building local loops and linkages	Energy-efficiency (off-farm): supply chain
	Building local loops and linkages	Energy-efficiency (on-farm): irrigation practices, food storage/refrigeration, other
	Building local loops and linkages	On farm electric vehicles
	Scaling productive and regenerative agriculture	Modify feed composition to reduce emissions (e.g. supplement/replace feedstock with red algae)
	Scaling productive and regenerative agriculture	Increase capacity to capture major rainfall events, e.g. larger head-water storages

Climate change adaptation	Scaling productive and regenerative agriculture	Climate resilient crop varieties (i.e. yields and irrigation requirements resilient to climate change impacts)
Conservation agriculture	Scaling productive and regenerative agriculture	Organic farming
	Scaling productive and regenerative agriculture	Regenerative agriculture (e.g. ecological grazing; no-till; agroforestry; pasture cropping; silvopasture; syntropic agriculture)
Crop management practices	Scaling productive and regenerative agriculture	Alley cropping: production trees planted in alleys among row crops (agroforestry)
	Scaling productive and regenerative agriculture	Conservation cropping: use of no-till practices (including chemical no-till)
	Scaling productive and regenerative agriculture	Reduced till
	Scaling productive and regenerative agriculture	Conservation cropping: crop rotation
	Scaling productive and regenerative agriculture	Longer rotations / delay harvest of plantations
Crop prioritisation/selection	Scaling productive and regenerative agriculture	Replacing annual crops with perennial crops
	Scaling productive and regenerative agriculture	Increased perennial horticulture
	Scaling productive and regenerative agriculture	Production of trees that produce staple crops (starch, protein, oils) and fibre, to replace some annual cropping with trees providing bio-sequestration
Diversifying sources of animal protein	Investing in diversified sources of protein	Novel alternative proteins - aquaculture
	Investing in diversified sources of protein	Novel alternative proteins - fungi
	Investing in diversified sources of protein	Novel alternative proteins - insect derived protein fed on food waste
	Investing in diversified sources of protein	Novel alternative proteins -lab meat
	Scaling productive and regenerative agriculture	Shift from ruminant to monogastric production (off-land)
	Investing in diversified sources of protein	Novel alternative proteins - microbial protein
	Investing in diversified sources of protein	Cellular agriculture
	Investing in diversified sources of protein	Novel alternative proteins - plant protein
	Investing in diversified sources of protein	Increase consumption of alternative protein sources, e.g. natives, feral animals
Farm management practices	Scaling productive and regenerative agriculture	Conservation cropping: cover crops enabling more efficient use of synthetic fertilisers and pesticides
	Scaling productive and regenerative agriculture	Pasture cropping
	Scaling productive and regenerative agriculture	Shelterbelt plantings (Woody perennials (native / non-native) for shelter, fibre, water quality, land rehabilitation, fodder bank, and/or habitat)
	Scaling productive and regenerative agriculture	Silvopasture: production trees in a pasture / livestock system (agroforestry)
Increased crop productivity	Scaling productive and regenerative agriculture	Reduce GHG emissions from crops (nitrous oxide emissions from crops, e.g. with nitrification inhibitors)

	Harnessing the digital revolution	Digital agriculture
	Harnessing the digital revolution	Increase crop productivity, e.g biotechnology, gene mapping/editing, enhanced management practices
	Scaling productive and regenerative agriculture	Integrated pest management (resulting in decreased use of pesticides)
	Scaling productive and regenerative agriculture	Increased irrigation and water use efficiency
	Scaling productive and regenerative agriculture	Increase nutrient use efficiency, e.g. enhanced nutrient management strategies, slow release fertilisers to cut N and P losses from cropping and grazing enterprises
	Scaling productive and regenerative agriculture	Increase pasture productivity, e.g. high-yielding forage grasses
	Harnessing the digital revolution	Precision Agriculture: Reduce input requirements and chemical residue and increase output through precision application, enabled by new digital tech (e.g. sensors, AI and machine learning, automation and drones)
Increased livestock productivity	A healthy and productive ocean	More efficient aquaculture
	Scaling productive and regenerative agriculture	Reduce GHG emissions from livestock, e.g. via feed supplements, breeding, pasture techniques, biological controls
	Scaling productive and regenerative agriculture	Modify feed composition, e.g. reduce grains fed to livestock
Nutrient enrichment	Building local loops and linkages	Compost application
	Scaling productive and regenerative agriculture	Green manure
Other non-land	Building local loops and linkages	Urban and peri-urban farming
	Scaling productive and regenerative agriculture	Protected agriculture (e.g. hydroponics, vertical farming)
Protecting and restoring nature	Protecting and restoring nature	Improve connectivity between protected areas and non-protected areas
	Protecting and restoring nature	Fire risk management for ecological outcomes (carbon stocks, biodiversity, traditional knowledge)
	Protecting and restoring nature	Waterway and floodplain rehabilitation (including flow regimes)
	Scaling productive and regenerative agriculture	Manage "total grazing pressure", i.e. reduction of cumulative grazing pressure from kangaroos, ferals and livestock.
	Protecting and restoring nature	Improved ecological management of protected areas and non-protected areas
	Protecting and restoring nature	Expand protected areas
	Protecting and restoring nature	Protect and manage riparian zones, e.g. fence out or control stock from dams, wetlands & waterways
		Minimise run-off of sediments, chemicals and nutrients
	Protecting and restoring nature	Wetland creation / rehabilitation / protection
	Reducing food loss and waste	Reduce food waste at end use (food service, households, retail)

Reduced food & fibre loss and waste	Reducing food loss and waste	Reduce food losses on farm, e.g. due to market conditions, quality standards, labor challenges, pest infestations or weather
	Reducing food loss and waste	Reduce food waste in downstream value chain (processing / manufacturing, transport)
Securing a healthy and productive ocean	Securing a healthy and productive ocean	Mangrove rehabilitation / protection
	Securing a healthy and productive ocean	Seagrass rehabilitation / protection
	Securing a healthy and productive ocean	Shellfish reef restoration
	Securing a healthy and productive ocean	Tidal marshes restoration / protection
Shift towards healthy and sustainable diets	Promoting healthy diets	Shift to more plant-based diets
	Promoting healthy diets	Reduced discretionary foods (sugar / grain consumption) to healthy levels.

Table 2. Co-produced indicators database. Indicators have been aligned to the appropriate Sustainable Development Goals (SDGs), described, and situated within the SDGs Wedding Cake framework (Sukhdev & Rockström, 2016)*.

SDGs Wedding cake category	**SDG**	**Indicator**	**Description**
Economy	SDG8 Decent work and economic growth	Total economic contribution	The food and land use system is contributing to the national GDP/trade balance
	SDG8 Decent work and economic growth	Economic diversification and resilience	The food and land use economy is increasingly diversified and resilient
	SDG8 Decent work and economic growth	Regional community economic development	Farmers, foresters, and land managers have good livelihoods, underpinning thriving regional economies and communities
	SDG12 Responsible consumption and production	Productivity	The food and land use system is efficient and productive
	SDG12 Responsible consumption and production	Natural resource intensity	The food and land use system is efficient in its use of natural resources

	SDG12 Responsible consumption and production	Waste and Loss	Loss and waste of food and fibre is minimised, and unavoidable waste is reused
	SDG12 Responsible consumption and production	Agricultural inputs	Nutrient inputs are sourced sustainably and used efficiently
	SDG12 Responsible consumption and production	Humane treatment of animals	Australian agriculture ensures humane treatment of animals
Society	SDG2 Zero hunger & 3. Good health and wellbeing	Healthy diets	The food and land use system increasingly contributes to secure, accessible and healthy diets
	SDG3 Good health and wellbeing	Health and wellbeing	Regional communities have good health and wellbeing
	SDG7 Affordable and clean energy	Renewable energy	The food and land use system contributes to decarbonisation of other sectors by exporting renewable energy
Biosphere	SDG13 Climate action	Emissions	Emissions from the food and land use system are reduced
	SDG13 Climate action	Sequestration	The food and land use sector puts carbon back in the landscape through biomass and soils
	SDG6 Clean water and Sanitation	Water efficiency	Water use is efficient and adaptive
	SDG6 Clean water and Sanitation	Water quality	Water quality is maintained or improved
	SDG14 Oceans & 6.	Water sustainability	Water use is within sustainable limits and water returned to the environment is sufficient to support biodiversity
	SDG15 Life on land	Biodiversity	Biodiversity is increasing
	SDG15 Life on land	Soil	Soil health and function is improving

*The SDGs Wedding Cake (Stockholm Resilience Centre, 2016) is a way of conceptualising how healthy and sustainable food directly or indirectly connects all SDGs by viewing the social, economic, and ecological aspects of the SDGs.

Table 3 Tabular summary of solutions-indicator interactions for each solution category. Percentage values (%) represent the proportion of solutions coded under each 7-point scale category, this table aims to reflect the spread of synergies and trade-offs across solution categories and highlight priority solution categories and categories with trade-offs. Where there are no solution-interactions coded, cells are left blank.

Solution category	Major trade-off %	Moderate trade-off %	Minor trade-off %	No interaction %	Minor synergy %	Moderate synergy %	Major synergy %
Boost fibre production			24.0	3.0	2.1	0.9	
Breakthrough technologies				2.3	5.1	5.6	1.9
Carbon sequestration			44.0	5.7	6.0	5.2	5.8
Circular economy & energy decarbonisation			8.0	16.2	7.5	8.6	17.3
Climate change adaptation				2.8	3.2	1.3	
Conservation agriculture				1.1	2.6	5.2	7.7
Crop management practices				6.8	7.9	4.3	
Crop prioritisation/selection				3.6	4.3	4.7	
Diversifying sources of animal protein				2.7	2.8	2.6	
Farm management practices				6.2	7.0	7.8	
Increased crop productivity				9.4	11.7	10.8	7.7

Increased livestock productivity		100.0	4.0	5.2	6.0	3.0	3.8
Novel sources of protein			4.0	8.4	7.9	7.8	
Nutrient enrichment				1.4	3.4	4.3	
Other non-land				2.8	2.8	2.2	
Protecting and restoring nature			8.0	14.2	6.8	11.2	34.6
Reduced food & fibre loss and waste				2.0	4.5	6.0	9.6
Securing a healthy and productive ocean				4.1	5.8	6.0	7.7
Shift towards healthy and sustainable diets			8.0	2.1	2.6	2.59	3.8
Total	**0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table 4. Tabular summary of solution-indicator interactions across Sustainable Development Goals (SDGs). Percentage values (%) represent the proportion of solutions coded under each 7-point scale category. Where there are no solution-interactions coded, cells are left blank.

Sustainable Development Goal (SDG)	Major trade-off %	Moderate trade-off %	Minor trade-off %	No interaction %	Minor synergy %	Moderate synergy %	Major synergy %
SDG 2: Zero Hunger and/or SDG 3: Good Health and Well-being			8.0	14.8	11.8	3.4	
SDG 6: Clean Water and Sanitation and/or SDG 14: Life Below Water			32.0	14.2	18.8	14.2	25.0
SDG 7: Affordable and Clean Energy				12.5	0.4	1.7	3.8
SDG 8: Decent Work and Economic Growth			20.0	16.4	22.0	8.6	
SDG 12: Responsible Consumption and Production		100.0	8.0	27.8	26.3	31.5	34.6
SDG 13: Climate action			4.0	6.4	9.8	25.4	15.4
SDG 15: Life on Land			28.0	8.0	10.9	15.1	21.2
Total	**0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

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