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 impact. 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 (Foley et al. 2011; Campbell et al. 2017; Sukhdev 2018; IPCC 2019). Global demand for agricultural goods is expected to increase further with population and income growth (Crist et al. 2017; FAO 2018). 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 (Springmann et al. 2018; Willett et al. 2019; Clark et al. 2020). While a food and land system transformation has been defined and modelled at the global level (Searchinger et al. 2018; 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. The pathway towards food and land system transformation at the national level is not clearly defined (Sukhdev et al. 2016; Béné et al. 2019b), and there is a need for national-scale frameworks to prioritise solutions that can deliver the best outcomes to meet global Sustainable Development Goals (SDGs).

Achieving 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 (Searchinger et al. 2018; Springmann et al. 2018; Béné et al. 2019a; NFF 2019; Roe et al. 2021; McRobert et al. 2022; Mosnier et al. 2022; CSIRO 2023). Several studies have highlighted the need to move beyond a focus on productivity or single-paradigm approaches (Dornelles et al., 2022; Lindgren et al., 2018; Sukhdev, 2018), suggesting a shift to a systems approach to 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. Jones et al. 2016; Willett et al. 2019; Stefanovic et al. 2020; Fanzo et al. 2021; Hebinck et al. 2021), for supporting decision-making and the implementation of solutions for system transformation (TEEB 2018; Béné et al. 2019a; Silva et al. 2022). Australian-specific sustainability frameworks identifying indicators and roadmaps for sustainable food and agriculture system have been developed (McRobert et al. 2022; CSIRO 2023), 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).

The sustainable transformation of food and land systems requires the rapid implementation and scaling up of a broad suite of solutions to meet global SDGs. Sustainability solutions relevant to the food and land system include behaviour-oriented (broadly consistent with an emphasis on demand-side solutions), technology-driven (emphasis on supply-side solutions) as well as other emerging paradigms such as agroecology (Röös et al. 2017; Béné et al. 2019a) and novel proteins/novel foods (Herrero et al. 2020). The debate on which solutions should be prioritised depends heavily on the choice of indicators selected to assess the sustainability performance of the system (Garnett 2014). There are diverse views on the choice and weighting of different indicators, which diverge even more at regional and national scales (Bennett et al. 2021). To manage for this at the national and sub-national scale, geographic and spatial contexts and key stakeholders must guide the development of locally relevant indicators and solutions to better capture the local specificity of food and land systems (Béné et al. 2019a; Moallemi et al. 2020; Moallemi et al. 2021; Szetey et al. 2021; Bandari et al. 2022).

There is a need for appropriate frameworks to prioritise solutions to then support the focused development of integrated models, highlight knowledge and technology gaps, pathway development for scenario modelling exercises, and to inform policy (Nilsson et al. 2016; Nilsson et al. 2018). 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 (Béné et al. 2019b).

System level transformations require transdisciplinary collaboration across a broad range of stakeholders (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; Wyborn et al. 2019; Reed et al. 2022) and result in context-specific knowledge and sustainable pathways (Mauser et al. 2013; Norström et al. 2020; Chambers et al. 2021). The value of co-produced knowledge is well established in the field of sustainability science (Jassanoff 2004; Moallemi et al. 2020; Moallemi et al. 2021) leading to mutually reinforcing and reciprocal outcomes that represent more inclusive, legitimised, impactful, and systemic change for local contexts (Jassanoff 2004; Wyborn et al. 2019; Norström et al. 2020; Schneider et al. 2021). As such, adopting co-production methods can improve the integration of environmental, social, economic, and cultural factors into conceptualising system sustainability, and support navigating synergies and trade-offs in a just, transparent, and efficient manner (Béné et al. 2019b; 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) (Griggs et al. 2017; Allen et al. 2019; 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.

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 (ABS 2020-21; ABARES 2022), 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 (Grundy et al. 2016; Béné et al. 2019a). 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 et al. 2016), and facilitating shifts towards sustainable diets and food waste reduction (Springmann et al. 2018; Willett et al. 2019; Geyik et al. 2022). 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).

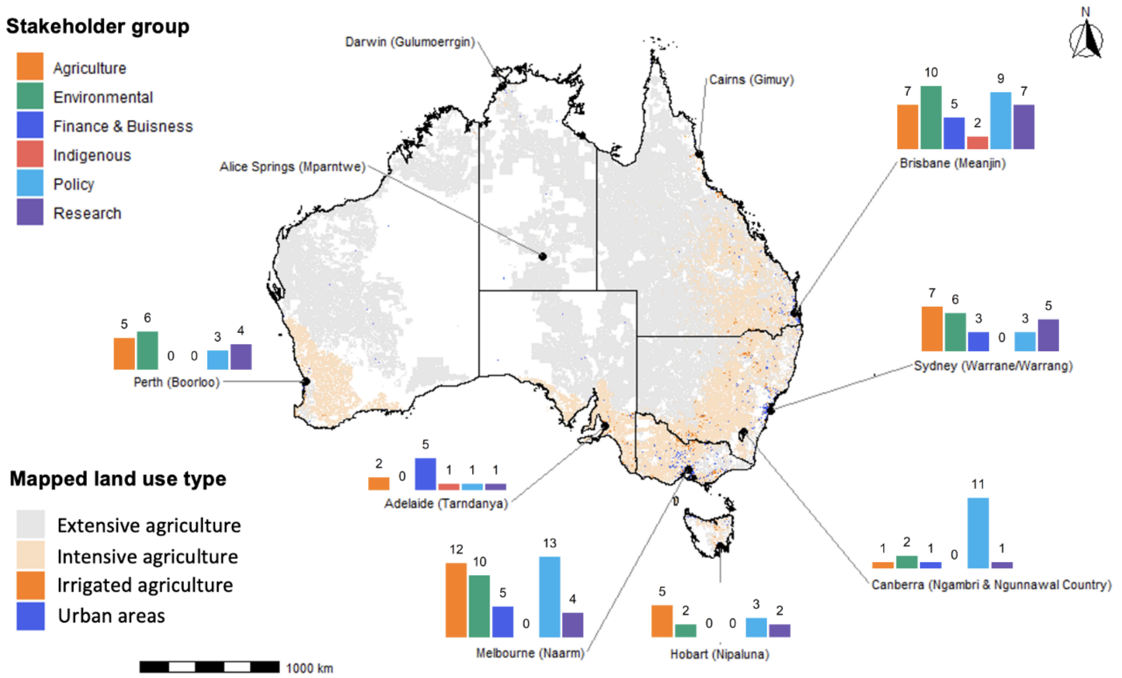

Figure 1. Agricultural land use map for Australia, displaying areas under extensive grazing, intensive grazing, cropping and horticulture as well as urban areas, with State and territory administrative boundaries overlayed. The bar graphs display the number of individuals involved in this project within each stakeholder groups for each major city co-production workshop.

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.

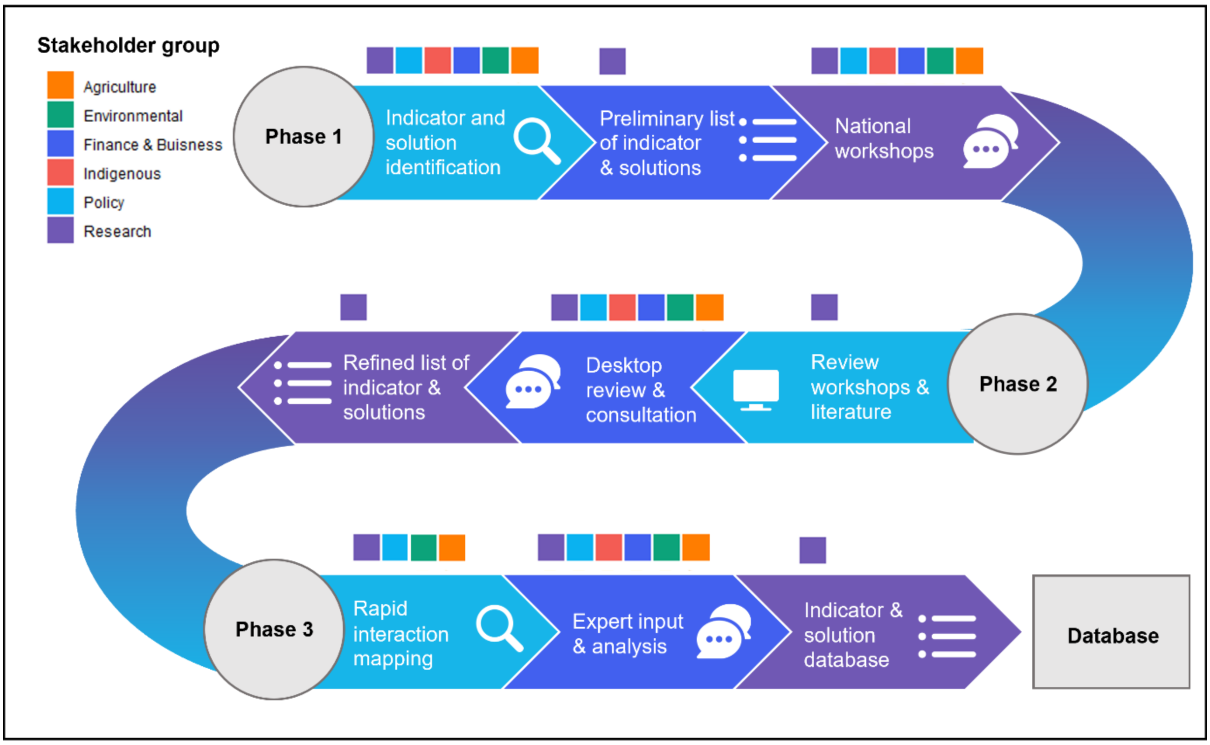

Figure 2. Visual representation of the process used to develop the knowledge co-production framework for identifying indicators and prioritising solutions. Coloured squares represent stakeholder engagement. Along the pathway light blue represents processes, deep blue represents inputs and purple represents outputs and goals. Icons are designed by Freepik from Flaticon.

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 and Bryan 2017).

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 150 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 S1 Supplementary Information). 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 (Supplementary Information 2). 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 S2, Supplementary Information 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 (Nilsson et al. 2018; Allen et al. 2019; Hopkins et al. 2021). Levels of synergy and trade-off are defined in Figure 3 (Nilsson et al. 2016; Nilsson et al. 2018). 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.

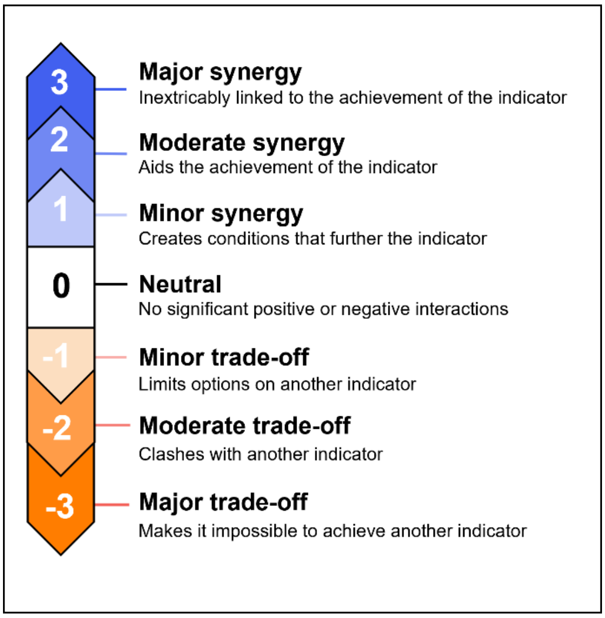

Figure 3. Rapid interaction mapping coding classes: adapted 7-point scale (Nilsson et al., 2016).

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 and scale), 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) 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 (Team 2020; Quatto and Ripamonti 2022). Disagreements were discussed to reach an agreement across all sub-sample solution-indicator interactions prior to progressing to screening all interactions.

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 4). 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. 1997; Hill et al. 2005). 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 sustainability indicators that mapped to 9 SDG domains, and 78 sustainability solutions categorised into 19 broader solution categories to support the sustainable transformation of the Australian food and land system. The full solutions and indicators database are located in Supplementary Information 2.

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. Photo credit ClimateWorks Centre.

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 and 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 Materials 3.

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 Materials 3: 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 1).

The solution category 'Protecting and restoring nature' had the highest number of major synergies (34.6%, Table 1.) 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 1.) 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.

Table 1 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 no solution-interactions were 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 2. 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 no solution-interactions were 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**

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 2). 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 1): '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 1) 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 2), and no major trade-offs were identified among solution-indicator interactions (impossible to achieve other indicators) (Table 1).


Sustainable Development Goals and Sustainability Indicators
Individual solutions
2 & 3
Health and wellbeing
Healthy diets
6 & 14
Water efficiency
Water quality
Water sustainability
7
Renewable energy
8
Economic contribution
Economic diversification
Regional development
12
Agricultural inputs
Animal welfare
Resource intensity
Productivity
Waste and loss
13
Carbon emissions
Carbon sequestration
15
Biodiversity
Soil
Food technologies
Gene technology
Innovative inputs
BECCS
Biochar
Bioenergy (Grasses)
Bioenergy (Plants)
Carbon plantings
Biofuel and biogas (Farm)
Farm electric vehicles
Farm energy-efficiency
Farm renewable energy
Feed emissions
Food waste to fuel
Manure management
Off-farm energy-efficiency
Recycled nutrients
Capturing rainfall
Climate resilient crops
Organic farming
Regenerative agriculture
Fire risk management
Grazing pressure
Habitat connectivity
Habitat management
Minimise run-off
Protecting areas
Riparian conservation
Waterway rehabilitation
Wetland conservation
Mangrove conservation
Marsh conservation
Seagrass conservation
Shellfish reef restoration
Alley cropping
Crop rotations
Longer rotations
No till
Reduced till
Crop productivity
Digital agriculture
Nutrient use efficiency
Pasture productivity
Pest management
Precision Agriculture
Reduce crop emissions
Water use efficiency
Less annual crops
Perennial horticulture
Staple crops and trees
Alternative proteins
Aquaculture
Agroforestry
Cover cropping
Farm diversification
Pasture cropping
Shelterbelt plantings
Plantation timber
Production forestry
Aquaculture
Livestock emissions
Monogastric production
Supplement composition
Downstream food waste
Food loss (Farm)
Food waste (End use)
Cellular agriculture
Fungi
Insect protein
Lab meat
Microbial protein
Plant protein
Compost application
Green manure
Protected agriculture
Urban farming
Discretionary foods
Plant-based diets
Major trade-off
Moderate trade-off
Minor trade-off
Neutral
Minor synergy
Moderate synergy
Major synergy

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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 (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 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). Icons on the right-hand side represent the solution category groupings.

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 2 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 (Grundy et al. 2016; Nilsson et al. 2016; Griggs et al. 2017; Pradhan et al. 2017; Nilsson et al. 2018; van Soest et al. 2019; Bandari et al. 2022), 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 et al. 2019a).

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 (Steinfeld and Gerber 2010; Gerber et al. 2013), 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 (Seddon et al. 2020; Keith et al. 2021; Miralles-Wilhelm 2021), 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 (Moallemi et al. 2021; Szetey et al. 2021; Bandari et al. 2022) and informed by the intended scale of application (Nilsson et al. 2016; Gao and Bryan 2017).

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. Stoy et al. 2018; Withey et al. 2019; Cobo et al. 2022) which are highly context and site specific (Donnison et al. 2020).

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 and 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 and Sriwannawit 2015). This finding may also reflect the exclusion of transportation and refrigeration of goods/products from the scope of this study, where some of the greatest opportunity for decarbonisation and the adoption of renewable energy solutions are currently available (AEC 2022). 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

While the need for food system transformation is universally accepted (Willett et al. 2019; Rockström et al. 2020; Webb et al. 2020; Fanzo 2021; Hebinck et al. 2021), the pathway towards transformation is not clearly defined (Sukhdev et al. 2016; Béné et al. 2019b). 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. 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 (Jasanoff and Kim 2015; Chabay et al. 2021; 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 and 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, trans-boundary, and 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 two 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 (Moallemi et al. 2021; Szetey et al. 2021; Bandari et al. 2022), we cannot be certain that an even representation of stakeholders and opinions was achieved during 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 for their indicated 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. Quantification of impacts (or technical potential) is often only possible for a subset of the total number of solutions considered in qualitative narratives and may entail some inevitable simplification, hence it is important for the 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., Nielsen et al. 2020; Brutschin et al. 2021) 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.

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.

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Author contributions

Study conception and design was performed by M. Hadjikakou, C.L. Archibald, R.L. Zyngier, B.A. Bryan, M. Elliot. Material preparation, data collection and analysis were performed by C.L. Archibald, R.L. Zyngier, M. Hadjikakou, H. Lambert. Additional data collection and analysis was provided by L. Gao, M. Lawrence, L. Bennett, T. Reeves, M. Pryor, U. Lindholm, S. Oaken, S.J. Williams-Watts, G. Gale, and J. Hutchinson. C.L. Archibald prepared the figures. The first draft of the manuscript was written by R.L. Zyngier, C.L. Archibald, E.A. Moallemi and M. Hadjikakou and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Table of contents: Supplementary Information

Supplementary Information 1: Phase 1

National workshop methodology and outputs

In 2019, we carried out a series of workshops in every capital city except for Darwin (Northern Territory), and with a more specific, government-targeted workshop in the federal capital Canberra (Australian Capital Territory). A total of 7 workshops were held between March and May 2019 in person, and the full series included over 150 people from almost 100 organisations. Workshop attendees included landowners, agricultural industry representatives, sustainable agriculture consultants and advisors, finance and investment, federal and state government policy makers, natural resource managers and research/advisory and development organisations.

Workshop participants were engaged in three working group sessions over the course of a day. The first session established the context for the day, during which individuals were invited to share or write down individual perspectives on: defining success in their work or practice; the biggest risks and uncertainties they face now and in the future; and one thing that would help accelerate or scale-up their work. Common themes were identified and shared back with the wider participant group. In the second working group session workshop participants were presented with the candidate lists of indicators and were invited to provide feedback using sticky notes on a feedback matrix indicating what they liked (are there solutions/indicators you think are most important? Why are they important?); wanted to add (are there solutions/indicators missing? What would you add?); wanted to remove (are there solutions/indicators you think are not important or should not be there?); or had questions or comments about (do you have any questions? Overall or about a specific solution/indicator?).

In the third working group session workshop participants were presented with the candidate list of solutions and were invited to provide feedback using sticky notes on a feedback matrix indicating what they liked (are there solutions/indicators you think are most important? Why are they important?); wanted to add (are there solutions/indicators missing? What would you add?); wanted to remove (are there solutions/indicators you think are not important or should not be there?); or had questions or comments about (do you have any questions? Overall or about a specific solution/indicator?). Following the workshops, we collated data collected during workshop sessions two and three. The workshop series resulted in: a total of 496 comments on solutions and 478 comments (sticky notes) 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. Sticky notes were analysed using Nvivo13 (2020, R1) (Lumivero 2020) to produce word clouds to show priority indicators and solutions as identified by stakeholders (Figure S1). System actor input was incorporated into the candidate lists to form a draft co-produced solutions and indicators database.

Figure S1. Word clouds generated for indicators (A) and solutions (C) to analyse sticky notes from the 2019 workshops (B, example workshop outputs) to show priorities as identified by stakeholders.

Supplementary Information 2: Phase 2 Indicators and solutions database

Indicators database

Table S1 is the final list of 18 co-produced indicators that constitutes the indicators database. This final list was developed and refined during phases 1 and 2. This indicators database provides the final list of co-produced indicators for describing a sustainable food and land use system for Australia. These nationally relevant (locally specific) indicators are mapped to SDGs and are described. These locally specific indicators differ to solution categories which summarise or bundle land use or behaviour practice change.

Table S1. Co-produced indicators database. Indicators have been aligned to the appropriate Sustainable Development Goals (SDGs) and described.

SDG	Indicator	Description
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
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
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

SDG	Indicator	Description
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
SDG7 Affordable and clean energy	Renewable energy	The food and land use system contributes to decarbonisation of other sectors by exporting renewable energy
SDG15 Life on land	Biodiversity	Biodiversity is increasing
SDG15 Life on land	Soil	Soil health and function is improving
SDG14 Oceans & 6. Water	Water sustainability	Water use is within sustainable limits and water returned to the environment is sufficient to support biodiversity
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

Solutions database

Table S2 is the final list of 78 solutions that constitutes the co-produced solutions database. This final list was developed and refined during Phases 1 and 2. This solutions database provides the final list of co-produced solutions for achieving a sustainable food and land use system for Australia and indicates which high-level solution category each solution has been allocated to.

Table S2 is the final list of 78 solutions that constitutes the co-produced solutions database. This final list was developed and refined during Phases 1 and 2. This solutions database provides the final list of co-produced solutions for achieving a sustainable food and land use system for Australia and indicates which high-level solution category each solution has been allocated.

Table S2. Co-produced solutions database. Solutions are grouped by solution category and are described with examples. Solution descriptions indicate what is included and excluded from the solution within the context of this study. References are provided for solution descriptions where relevant.

Solution Category	Solution	Description and examples	Reference
Boost fibre production	Production forestry (timber, high-value timber)	Commercial tree growing (timber plantation industry) in plantations to produce timber products, excluding timber grown of farms.	DAWE (2022)
	Increase use of plantation timber in buildings and materials (demand shift)	Increasing proportion of Australian-grown plantation timber in building materials, in replacement of non-wood building materials. This solution does not include timber imported into Australia from overseas used as building materials.	
Breakthrough technologies	Food processing and safety technologies to reduce food loss and waste	The use of technologies to extend the shelf-life of food products including: biodegradable water or oil-based coatings to surface of crops; application of microorganisms to reduce post-harvest loss; use of nanocomposites for food packaging; low-energy processing technologies to extend food shelf-life; drying and stabilising technologies; whole-genome sequencing to identify and predict food safety hazards; food safety technologies designed to inhibit microorganism growth.	Herrero et al. (2020)

Solution Category	Solution	Description and examples	Reference
	Gene technology	Use of a variety of innovative food technologies falling under the category of 'gene technology', including synthetic biology (enabling machines to produce biological materials at low-cost and with minimal inputs); novel N-fixing crops (via gene transfer to new crops from legumes); novel perennials (using gene tech / breeding to create temperate-adapted perennial grain crops); biofortified crops; disease / pest-resistant crops; crops that can compete better against weeds; crops with higher numbers of desirable traits due to genome-wide selection; asexual crop reproduction via seeds; development of novel oils in crops for human consumption and petrochemical replacement; reconfiguration of photosynthesis; genome editing; GM assisted domestication; RNAi gene silencing; genomic selection (source: Herrero et al. 2020, Supp materials pp.23-25)	Herrero et al. (2020)
	Innovative agricultural inputs, (e.g., botanicals, enhanced efficiency fertilizers, holobiomics, macrobials, micro-irrigation/fertigation, microbials, nanoenhancers, nanofertilizers, nanopesticides, soil additives)	Innovative agricultural inputs are new and emerging technologies that optimise and improve efficiency and overall productivity of crops. Inputs include: soil additives that optimise water use or increase soil fertility to assist plant growth; use of micro-irrigation, fertiliser, or fertigation systems to optimise water and nutrient use; use of nanofertilisers to increase nutrient-use efficiency via targeted delivery; enhanced efficiency fertilisers that are smart controlled release to match release of nutrient to the plant stage; nanopesticides to control pests and avoid some of the drawbacks associated with traditional pesticides; nanoenhancers (e.g. CuO and ZnO nanoparticles) to enhance crop performance (source: Herrero et al. 2020, Supp materials pp.21-22)	Herrero et al. (2020)
Carbon sequestration	Biochar	Biochar is a stable, carbon–rich charcoal-like product made by heating organic materials (e.g., crop waste, grass, woodchips and manure) in a high temperature, low oxygen combustion process termed pyrolysis. The application of the biochar to soil to increase soil carbon, soil fertility, water holding capacity and crop productivity.	Sohi et al. (2010)
	Bioenergy from perennial grasses and coppiced woody plants for feedstock (including BECCS)	The growth and harvesting of perennial grasses or trees and coppiced woody plants (i.e., periodically cut) to generate bioenergy and CO2 capture and long-term storage. This includes bioenergy carbon capture and storage (BECCS), a carbon-negative technology that combines sustainable bioenergy conversion with CO2 capture and storage.	Quader and Ahmed (2017)

Solution Category	Solution	Description and examples	Reference
	Bioenergy from crop residue (non-BECCS)	The use of crop residue (e.g., straws of cereal and corn) to generate bioenergy either through thermo-chemical or biological techniques	Jiang et al. (2012)
	Bioenergy from woody perenials (non-BECCS)	Growth and harvesting of perennial grasses or trees, and coppiced woody plants (i.e., periodically cut) to generate bioenergy, either through gasification-based combined cycle (IGCC), combustion-based steam cycle, and gasification-based gas engine.	Lemus and Lal (2005)
	Carbon plantings (monoculture species)	The establishment of fast-growing single species (monoculture) plantations for carbon sequestration with the aim of selling this stored carbon as a carbon credit.	Kanowski and Catterall (2010)
Circular economy & energy decarbonisation	On farm biofuel and/or biogas production/use	On-farm conversion of feedstocks into biofuels (biodiesel, biogas, or ethanol) for use as on-farm energy.	Quader and Ahmed (2017)
	Food waste to fuel	Using food waste to generate energy through waste-to-energy processes, which generate electricity and heat, but also produce GHGs (CO2, NOx, MH4) as by-products.	Australian Academy of Science (2020)
	Improve manure management (compost and bioenergy) in intensive systems (e.g., dairy; pigs and poultry)	Compost: Composting to reduce methane emissions from livestock manure. Bioenergy: Use a biogas generation system to digest large volumes of manure under low-oxygen conditions. This produces biogas that is subsequently combusted to destroy methane and produce heat or electricity. The waste sludge is normally returned to the land as fertiliser, either as slurry or pellets. (Source: WA DIPRD 2020)	DIPRD (2021)
	Recycled organic nutrients from urban waste streams (compost from green waste; bio-solids)	Compost from green waste: Processing of food and organic waste (FOGO) to create compost. Biosolids: biosolids are one of the products created as a result of processing sewage. Biosolids can be used on farmland to improve soil, as well as in compost and fertiliser. Note: Excludes manure from feedlots, as this solution is focused on 'urban' waste	DAWE (2020)
	Renewable energy generation (and storage) on farm for electricity.	Generation of renewable energy on-farm using wind, solar PV, solar thermal e.g. wind, solar, combined heat and power, microgrids and sharing on and between farms. Note: excludes generation of energy using biogas.	

Solution Category	Solution	Description and examples	Reference
	Energy-efficiency (off-farm): supply chain	Energy efficiency of supply chain of products and services upstream of the farm. For example, energy efficiency of production of agricultural inputs, such as fertiliser.	
	Energy-efficiency (on-farm): irrigation practices, food storage/refrigeration, other	Energy efficiency of all energy-using activities on-farm. This includes operation of farm machinery, electricity use by irrigation pumping systems, and on-farm storage of produce (before it leaves farm gate)	
	On farm electric vehicles	Use of electric machinery on farm in place of petrol or diesel-powered vehicles. This includes electric cars/trucks/utes and tractors.	
	Modify feed composition to reduce emissions (e.g., supplement/replace feedstock with red algae)	Reduction in methane emissions via feed stocks / dietary supplements that reduce the production of methane in the livestock's rumen (e.g., oils, fats, tannins, probiotics, nitrates, enzymes, marine algae and native vegetation) and forage plants that reduce methane emissions.	Honan et al. (2021)
Climate change adaptation	Increase capacity to capture major rainfall events, e.g., larger head-water storages	Development of new dam and other water storage infrastructure (e.g., Northern Australia) for use by agriculture, enabling expansion of farming to new, previously unfarmed areas.	
	Climate resilient crop varieties (i.e., yields and irrigation requirements resilient to climate change impacts)	The use of climate-resilient crops and crop varieties have enhanced tolerance to biotic and abiotic stresses with the aim of maintaining or increasing crop yields under stress conditions (droughts, floods, higher average temperatures, and other climatic conditions). For example, the adoption of climate-resilient crops such as early maturing cereal crop varieties, heat-tolerant varieties, drought-tolerant legumes or tuber crops, crops or varieties with enhanced salinity tolerance, or rice with submergence tolerance.	Acevedo et al. (2020)

Solution Category	Solution	Description and examples	Reference
Conservation agriculture	Organic farming	A production and management system which promotes and enhances agro-ecosystem health (soils, ecosystems, and people) and relies on ecological processes, biodiversity and landscape cycles adapted to local conditions. Emphasis is placed on the use of management practices (agronomic, biological, and mechanical methods) to replace off-farm inputs and synthetic materials, accounting for regional conditions requiring locally adapted systems.	FAO (1999)
	Regenerative agriculture	Regenerative agriculture is a system of farming principles that focuses on nurturing and restoring soil health, considered as a conservation and rehabilitation approach to food and farming	Rhodes (2017)
Crop management practices	Alley cropping: production trees planted in alleys among row crops (agroforestry)	A form of tree intercropping that specifically involves planting trees or hedges in closely spaced rows with crops grown in between. This reduces surface water runoff and erosion, improves soil health and fertility, reduces wind erosion, can add another cash crop to the system and sequester carbon. Depending on the crops selected, it can also modify the microclimate for improved crop production or improve wildlife habitat.	Project Drawdown
	Conservation cropping: use of no-till practices (including chemical no-till)	Farming practice that does not use mechanical tillage for the soil for crop establishment. Including control of weeds using herbicides	
	Reduced till	Farming practice that reduces the use of mechanical tillage for the soil for crop establishment. Including control of weeds using herbicides	
	Conservation cropping: crop rotation	Rotation of crops on an area. Ensure diseases of one crop cannot build up and the types of herbicides used for the weeds can be changed each year.	

Solution Category	Solution	Description and examples	Reference
	Longer rotations / delay harvest of plantations	Extension in length of rotations during production cycle of plantation timber forests to sequester carbon and provide other potential ecological value (rather than rotation lengths being determined purely by economic considerations).	Gong et al. (2019)
Crop prioritisation/selection	Replacing annual crops with perennial crops	Replacement of annual staple crops with perennial to increase overall carbon sequestration. Note: does not apply to horticultural crops - these are covered by RA-PHT. Applies to cereals	Project Drawdown
	Increased perennial horticulture	Replacement of annual horticulture crops with perennial to increase overall carbon sequestration. This most commonly relates to tropical crops, including tree staple crops like starchy fruits such as bananas and breadfruit, oil-rich fruits such as avocado, and nuts.	Project Drawdown
	Production of trees that produce staple crops (starch, protein, oils) and fibre, to replace some annual cropping with trees providing bio-sequestration	Replacement of some annual crops with productive trees that grow crops, aimed at increasing carbon sequestration while producing staple foods/ This is different to alley cropping / intercropping, because it is the complete replacement of crops with trees, rather than growth of these together.	Project Drawdown
Diversifying sources of animal protein	Novel alternative proteins - aquaculture	Commercial farming of finfish, molluscs, crustaceans and seaweed falling within the following categories: Offshore Longline and Rack Aquaculture, Offshore Caged Aquaculture, Onshore Aquaculture.	ABS (2006)
	Novel alternative proteins - fungi	Fungal-derived mycoprotein incorporated or processed into food products as a source of protein (source: Derbyshire & Delange 2021)	Derbyshire and Delange (2021)
	Novel alternative proteins - insect derived protein fed on food waste	The mass production of insects under controlled conditions, fed on food waste and used as protein supplements to animal feed or food for people.	Fowles and Nansen (2020)
	Novel alternative proteins -lab meat	The stem cells of a living animal are harvested and nurtured in the laboratory to create muscle tissue. Also commonly referred to as lab-grown, cultured, clean, cell-based, artificial, tissue-engineered, in-vitro, synthetic, animal-free and test tube meat.	Van Loo et al. (2020)

Solution Category	Solution	Description and examples	Reference
	Shift from ruminant to monogastric production (off-land)	A shift away from production of ruminant livestock for meat (primarily cattle) for protein for human consumption, and towards monogastric livestock production (primarily chicken and pigs) where feed is brought in from outside the farm e.g., intensive farming practices with high feed efficiency and low/no loss to the environment of water and nutrients.	
	Novel alternative proteins - microbial protein	The production of high-quality protein additives from microorganisms (single-cell protein) (source: Matassa et al. 2016)	Matassa et al. (2016)
	Cellular agriculture	Cellular agriculture is the use of cells and innovative biotechnologies to produce safe, accessible, ethical and sustainable food and agricultural products. It is commonly used to produce animal-derived foods and ingredients (e.g., meat, seafood, dairy products, fats, egg whites and gelatine) as well as non-animal products (e.g. palm oil)	Eibl et al. (2021)
	Novel alternative proteins - plant protein	Plant-based products that are alternatives to meat. Can comprise soy, pulses, jackfruit, mushrooms, wheat, or pea protein. It excludes mycoprotein.	Santo et al. (2020)
	Increase consumption of alternative protein sources, e.g., natives, feral animals	Consumption of wild-caught animal protein sources that are native to Australia (e.g., wallaby, kangaroo), or are currently introduced pest species (e.g., rabbit, deer)	
Farm management practices	Conservation cropping: cover crops enabling more efficient use of synthetic fertilisers and pesticides	Cover crop species grown to control weeds. After cover crop harvest, crop residue is applied on the ground to improve soil fertility and crop productivity by reducing runoff and erosion (source: Zhou et al. 2016)	Zhou et al. (2016)
	Pasture cropping	The planting of annual crops into perennial pasture for economic and environmental outcomes. Crops grazed directly, for additional feed for livestock.	Badgery and Millar (2009)

Solution Category	Solution	Description and examples	Reference
	Shelterbelt plantings (Woody perennials (native / non-native) for shelter, fibre, water quality, land rehabilitation, fodder bank, and/or habitat)	A vegetative barrier designed to reduce wind speed and provide sheltered areas on the leeward (the side away from the wind) and windward (the side toward the wind) sides of the shelterbelt. Benefits include protection of crops, livestock and the home, reduction of soil erosion, salinity control, improved biodiversity. In warmer months, shelterbelts can protect pasture and crops from moisture losses by reducing the impact of hot drying winds. Shelterbelts can also reduce erosion by wind.	DEECA (2020)
	Silvopasture: production trees in a pasture / livestock system (agroforestry)	A single strata of food trees with a herbaceous layer and animals integrated underneath.	Project Drawdown
Increased crop productivity	Reduce GHG emissions from crops (nitrous oxide emissions from crops, e.g., with nitrification inhibitors)	Reduction of emissions associated with fertiliser application to crops through techniques such as nitrification inhibitors and microbes that can allow crops to fix their own nitrogen. Other N-fixing techniques such as legumes as cover crops and nutrient use efficiency are covered by other solutions.	Waite and Rudee (2020)
	Digital agriculture	Use of agriculture technology (e.g., AI, big data, drones, IoT, robotics, sensors) to integrate agricultural production from the paddock to the consumer. These technologies can provide the agricultural industry with the tools and information to make more informed management decisions and improve productivity.	DEECA (2018)
	Increase crop productivity, e.g., biotechnology, gene mapping/editing, enhanced management practices	Increasing crop yields through management practices (e.g. fertiliser application, variety breeding), genetic engineering to improve productivity (e.g. virus resistance, drought tolerance), and genomes editing using CRISPR-Cas technology.	Bailey-Serres et al. (2019)
	Integrated pest management (resulting in decreased use of pesticides)	Controlling insect pests in agricultural production through the use of biological, cultural and chemical practices. For example, the use of natural predators or parasites to control pests, and only using selective pesticides when pests are unable to be controlled by natural means.	Stenberg (2017)

Solution Category	Solution	Description and examples	Reference
	Increased irrigation and water use efficiency	Improvements in water use efficiency (WUE), i.e., improvement in the amount of biomass produced per unit of water used by a plant, as well as improvements in efficiency of irrigation.	Hatfield and Dold (2019)
	Increase nutrient use efficiency, e.g., enhanced nutrient management strategies, slow-release fertilisers to cut N and P losses from cropping and grazing enterprises	Improving the efficiency of nutrient use (i.e., matching supply to crop/pasture demand, minimising loss of nutrients via the air and run-off) to improve yields. Techniques such as timing application of fertilisers to minimise loss, application of enhanced efficiency fertilisers (e.g., slow-release, or with nitrification inhibitors), use of chemical inhibitors to prevent nitrate leaching, and improved fertiliser application or delivery methods (e.g., application at the top of raised beds or ridges to avoid concentration and losses in furrows and wet areas).	DEECA (2021)
	Increase pasture productivity, e.g., high-yielding forage grasses	Management practices that improve pasture productivity. Practices may include rotational grazing, fertiliser application, irrigation, and use of higher-productivity pasture species.	
	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)	The use of technologies and tools to collect data on crop or animal performance and the attributes of individual production areas (e.g., fields, paddocks and blocks) at a high spatial resolution, to exert more control over a production system by recognising variation and managing different areas of land accordingly to meet a range of economic and environmental goals. Enabling technologies include GPS, soil sensors, yield monitors, drones.	Gebbers and Adamchuk (2010)
Increased livestock productivity	More efficient aquaculture	More efficient aquaculture requires an increase production of fish relative to the amount of land, water, feed, and energy used. There are many ways to achieve this such as: shifting energy supply to renewables; adoption of best practices to improve feed conversion ratios; shifting species mixes to those lower on the food chain; replacing fishmeal and fish oil for feed to crop-based ingredients, and technological innovation and adoption (breeding, feeds, production systems, disease control, and environmental management).	Waite et al. (2014)

Solution Category	Solution	Description and examples	Reference
	Reduce GHG emissions from livestock, e.g., via feed supplements, breeding, pasture techniques, biological controls	Reduction in methane emissions using techniques that reduce the production of methane in the livestock's rumen, and/or improve the conversion of feed to energy in livestock. Techniques include breeding to select for low methane emitting animals; biological controls (e.g., viruses) to attack methane producing gut microbes; dietary supplements (e.g., oils, fats, tannins, probiotics, nitrates, enzymes, marine algae and Australian native vegetation) and forage plants that reduce methane emissions. Note: Manure management techniques in intensive systems are covered by a different solution.	Toro-Mujica and González-Ronquillo (2021)
	Modify feed composition, e.g., reduce grains fed to livestock	Reduction of cereal feed production for livestock consumption (livestock are fed on grassland and by-products from food production only). This is to reduce competition for arable land for crops grown for human consumption.	Schader et al. (2015)
Nutrient enrichment	Compost application	Application of compost on-farm to soil to improve soil health	
	Green manure	Incorporation of existing green plant residue from previous crops into soil at cultivation. This is commonly done with an offset-disc plough. The aim of this solution is to kill weeds and control seedset with the co-benefit of building soil organic matter and nitrogen status. Cereal or pulse crops can be used for green manuring, or legumes can be used to further improve soil N content.	DPIRD (2021)
Other non-land	Urban and peri-urban farming	Growing food commercially in urban areas (cities and towns) and peri-urban areas (the interface between urban and rural areas).	
	Protected agriculture (e.g., hydroponics, vertical farming)	The production of horticultural crops within, under or sheltered by structures such as greenhouses, glasshouses, shade houses, screen houses and crop top structures. The intention is to provide modified/controlled growing conditions and/or protection from pests, diseases, and adverse weather.	NSW DPI

Solution Category	Solution	Description and examples	Reference
Protecting and restoring nature	Improve connectivity between protected areas and non-protected areas	Improvements to the degree in which the landscape facilitates movement of species among resource patches by improving the flow between protected and non-protected areas through landscape management and design. Improved connectivity supports conservation efforts to maintain landscape functionality and connectivity of habitat networks.	Taylor et al. (1993)
	Fire risk management for ecological outcomes (carbon stocks, biodiversity, traditional knowledge)	Fire management practices that avoid or minimise harm to the environment (air quality, land, water and biodiversity). The use of regime management to reduce the likelihood of occurrence and overall intensity of bushfire across the landscape; and maintain or improve biodiversity. Practices include both Indigenous and non-Indigenous management techniques.	Bull (2011)
	Waterway and floodplain rehabilitation (including flow regimes)	Rehabilitation of degraded waterways and floodplains using methods such as: pollution remediation; reinstating environmental flows; riparian and floodplain rehabilitation; targeted fish recovery and the removal of barriers to fish passage.	Bennett et al. (2002)
	Manage "total grazing pressure", i.e. reduction of cumulative grazing pressure from kangaroos, feral and livestock.	Reduction in grazing pressure exerted by all managed and unmanaged herbivores on the vegetation, soil, and water resources of rangeland landscapes. Strategies such as rotational grazing, culling, exclusionary fencing can be used to reduce grazing pressure.	Fisher et al. (2005)
	Improved ecological management of protected areas and non-protected areas	Ecological management techniques in protected and non-protected areas that improve ecological and biodiversity-focused indicators.	
	Expand protected areas	The expansion of Australia's network of protected areas that conserve landscapes, native plants and animals. This network is made up of national, state and territory reserves, Indigenous lands, and conservation areas which are run by conservation groups or individuals.	DCCEEW (2021)
	Protect and manage riparian zones, e.g. fence out or control stock from dams, wetlands & waterways	Management strategies that create healthy riparian zones, which support and maintain instream water quality, decrease bank erosion, increase bank stability and prevent soil loss within river systems. This can include exclusion of livestock from riparian areas using fencing and/or replanting riparian vegetation.	Malan et al. (2018)

Solution Category	Solution	Description and examples	Reference
	Minimise run-off of sediments, chemicals and nutrients	Minimising the amount of suspended solids and pollutants running off farms into waterways through strategies such as the application and matching of nutrients to crop requirements, minimum tillage, soil conservation, integrated weed management, control of stocking rates and minimising stock access to wetlands and waterways.	Department of Environment and Science (2022)
	Wetland creation / rehabilitation / protection	Creation, rehabilitation and protection of wetlands, for the purpose of restoration of environmental services, such as aquatic pollution remediation/ water filtration maintaining water supply, regulating atmospheric gases, carbon sequestration, flood abatement, habitat services, biodiversity conservation and cultural/recreational purposes.	Bennett et al. (2002)
Reduced food & fibre loss and waste	Reduce food waste at end use (food service, households, retail)	Reduction in food waste created at the end of the supply chain by: households; food retailers (supermarkets and other retailers); hospitality and food services (accommodation, restaurants, bars, cafes); and institutional food providers (residential aged care, childcare, healthcare, defences, correctional facilities).	ARCADIS (2019)
	Reduce food losses on farm, e.g. due to market conditions, quality standards, labour challenges, pest infestations or weather	Reduction in food loss at the point of primary production. This includes fruit & vegetables, nuts, wine grapes, crops, fisheries, eggs, livestock and milk. Loss can also occur due to spoilage, or if the product doesn't meet standards (including purely cosmetic) imposed on the producer by retailers or other along the supply chain.	ARCADIS (2019)
	Reduce food waste in downstream value chain (processing / manufacturing, transport)	Reduction in food waste after the point of primary production, but before it reaches the consumer. This includes manufacturing (e.g., fruit & vegetable processing, grain and cereal manufacturing, meat processing), transport and storage (both coldchain and ambient) and wholesale and distribution.	ARCADIS (2019)
Securing a healthy and productive ocean	Mangrove rehabilitation / protection	The protection of existing mangrove forests, or rehabilitation of degraded mangrove forests for the purpose of conservation, landscape rehabilitation, yield of sustainable products or protection of coastal areas.	Field (1999)

Solution Category	Solution	Description and examples	Reference
	Seagrass rehabilitation / protection	The protection of existing seagrass habitats, or rehabilitation of degraded seagrass habitats, including through passive restoration efforts such as the improvement of water quality by reducing runoff from agriculture or sewage outfalls.	Tan et al. (2020)
	Shellfish reef restoration	The protection of existing shellfish reefs, or rehabilitation of degraded shellfish reef habitats for the purpose of food provision, water filtration, fish production, coastal protection, and habitat for other species.	Fitzsimons et al. (2020)
	Tidal marshes restoration / protection	The protection of existing tidal marshes (also referred to as coastal wetlands), or rehabilitation of degraded tidal marshes for the purpose of aquatic and marine biodiversity enhancement, coastal and shoreline protection, marine life and fish habitat, and carbon sequestration.	Waltham et al. (2021)
Shift towards healthy and sustainable diets	Shift to more plant-based diets	A shift towards a diet with a greater consumption of wholegrains, vegetables and fruits, legumes, nuts and seeds, and avoids consuming most or all foods with animal origin.	Mbow et al. (2019)
	Reduced discretionary foods (sugar / grain consumption) to healthy levels.	Reduced consumption of food and drink that are not needed to provide nutrients the body requires. Many of these discretionary foods are high in saturated fats, sugars, salt and/or alcohol.	Hadjikakou (2017)

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Supplementary Information 3: Extended Results

The results of the Kappa analysis are that inter-rater agreement is 'moderate' (0.60). A moderate agreement level for this coding exercise is family acceptable due to the complexity. We also conducted Kappa analyses for each solution category to determine the inter-rater reliability within the category (Table S3).

Table S3. Kappa score across different solution categories across all solutions, is 'moderate' (0.60).

Solution category [a]	Kappa Score	Agreement Level
Building local loops and linkages	0.7	Moderate
Protecting and restoring nature	0.65	Moderate
Scaling productive and regenerative agriculture	0.6	Moderate
Diversifying sources of animal protein	0.58	Weak
Reducing food loss and waste	0.55	Weak
Securing a healthy and productive ocean	0.5	Weak
Shift towards healthy and sustainable diets	0.46	Weak

[a] Solution categories used in this preliminary stage of analysis were based on the FOLU solution categories (FOLU 2019). These solution categories were refined for all further analysis.

We also developed a simple approach to capture uncertainty. To represent uncertainty at a solution-indicator level, we calculated the difference between the maximum and minimum level assignment. A multidisciplinary team of experts across subject matters was assembled to provide additional rating of solution-indicator relationships with high uncertainty. There were only nine relationships (out of a total 1,404) which coding teams greatly disagreed on by a level of 4 (e.g., major synergy and minor trade-off), these required expert input to resolve. There were 66 relationships (out of a total 1,404) where disagreement was by a level of 3 (e.g., major synergy and neutral). We present the average relationship level, and report on the uncertainty clearly in the results in Table 2.

Table S4. The final range in uncertainty across the solution-indicator associations.

Level of uncertainty	**Major Synergy**	**Moderate Synergy**	**Minor Synergy**	**No interaction**	**Minor Trade-off**	**Moderate Trade-off**	**Major Trade-off**	**Total**	**Percent**
0	23	29	28	291	3			374	27%
1	29	116	211	258	13	1		628	45%
2		66	264	7	9			346	25%
3		21	29	6				56	4%

Solutions-indicator associations

Table S4 provides a summary of the solution-indicator associations, detailing the count and percentage of solutions associated with each indicator across all levels of synergy and trade-off. There were 52 unanimous major synergies identified between 31 solutions and 12 indicators (linked to 6 SGDs: 6, 7, 12, 13, 14, 15). These unanimous major synergies also had a high level of agreement between coders, as 18 of these solutions were coded as unanimous major synergies (with 0 disagreement) (Table 4) and 23 solutions with uncertainly of 1 level. Of these solutions, 12 were inextricably linked to the achievement of multiple indicators, and 19 were inextricably linked to one indicator.

Table S5. Summary of the spread of synergies and trade-offs across levels between solution-indicator associations.

	Major Synergy		Moderate Synergy		Minor Synergy		No Interaction		Minor Trade-off		Moderate Trade-off		Major Trade-off		Grand Total (n)
Solution category	n	%	n	%	n	%	n	%	n	%	n	%	n	%	
Conserving land	18	11	26	16	36	22	80	49	2	1					162
Circular economy	9	6	20	12	40	25	91	56	2	1					162
Loss and waste	5	9	14	26	24	44	11	20							54
Conservation agriculture	4	11	12	33	14	39	6	17							36
Conserving oceans	4	6	14	19	31	43	23	32							72
Crop productivity	4	3	25	17	62	43	53	37							144
Carbon sequestration	2	3	8	11	23	32	28	39	11	15					72
Livestock productivity	2	3	7	10	32	44	29	40	1	1	1	1			72
Shifting diets	2	6	6	17	14	39	12	33	2	6					36
Breakthrough tech	1	2	13	24	27	50	13	24							54
Nutrient enrichment	1	2	14	26	27	50	12	22							54

Climate adaptation	11	20	25	46	18	33							54
Crop management	10	11	42	47	38	42							90
Crop selection	11	20	23	43	20	37							54
Diversifying protein	8	15	24	44	22	41							54
Farm management	18	20	37	41	35	39							90
Fibre production	2	6	11	31	17	47	6	17					36
Novel protein	18	17	42	39	47	44	1	1					108
Other non-land	6	11	20	37	28	52							54

Table S6. Summary of the solutions with major synergies with SDGs.

6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	14 LIFE BELOW WATER	15 LIFE ON LAND
Mangrove rehabilitation and protection.	On farm biofuel and/or biogas production/use.	Regenerative agriculture.	Shift to more plant-based diets.	Increased irrigation and water use efficiency.	Expand protected areas.
Minimise run-off of sediments, chemicals, and nutrients.	Renewable energy generation on farm for electricity.	Minimise run-off of sediments, chemicals, and nutrients.	On farm biofuel and biogas production or use.	Waterway and floodplain rehabilitation	Improve connectivity between protected areas.
Protect and manage riparian zones.		Waterway and floodplain rehabilitation.	Reduce GHG emissions from livestock.	Wetland creation, rehabilitation, or protection	Improve management of protected areas.
Seagrass rehabilitation and protection.		Recycled organic nutrients from livestock manure and urban waste streams.	Renewable energy generation (and storage) on farm for electricity.		Carbon plantings (monoculture)
Shellfish reef restoration.		Recycled organic nutrients from urban waste streams.			Regenerative agriculture
Tidal marshes restoration and protection.		Increased irrigation and water use efficiency.			Fire management for ecological outcomes
Waterway and floodplain rehabilitation.		Organic farming			Minimise run-off of sediments, chemicals, and nutrients.
Wetland creation, rehabilitation, and protection		Improve manure management in intensive systems.			Protect and manage riparian zones.
		Reduce food waste in downstream value chain.			Waterway and floodplain rehabilitation
		Shift to more plant-based diets.			Wetland creation, rehabilitation, or protection

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