Knowledge co-production reveals nuanced societal dynamics and sectoral connections in mapping sustainable human-natural systems

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This is a preprint version of the article uploaded to EarthArXiv

This manuscript has been submitted to ***Earth's Future*** *and is under review.*

Key Points:

- Knowledge co-production used to map systems for sustainability assessment at the local scale
- Local scale co-produced systems mapping resulted in a stronger focus on societal elements than generally observed at larger scales
- Reflection identified strengths and weaknesses of the process, and facilitated understanding of the co-production types and modes involved

Abstract

The UN Sustainable Development Goals (SDGs) encompass environmental, social, and economic dimensions which are linked to the characteristics of place and have a strong local dimension. They are interconnected at local scales in complex ways which makes progress towards them difficult to predict. To understand how these interconnections play out at the local scale, we used knowledge co-production to undertake systems mapping for the purpose of sustainability assessment framed by the SDGs. We partnered with a local community in Australia as our co-production case study, with a multi-stage engagement process to understand how they interpreted sustainability, and their vision for a sustainable community. We found that co-developing a map of the local system with participants can elicit far more societal interconnections between the SDGs than might be expected without knowledge co-production, as the participants viewed the system through a social lens. Issues from the social dimension of sustainability, in particular, were intensely local in origin and effect which suggests that attempts to represent them at national or global scales are unlikely to succeed. We teased out the interconnections between societal and non-societal issues with local knowledge, which enhanced the ability to identify effective actions to tackle broader sustainability problems. Our results demonstrate that knowledge co-production can improve understanding of what sustainability is at the local scale and how it can be achieved, enabling the transformative change required to achieve the SDGs.

Plain Language Summary

The Sustainable Development Goals (SDGs) are a United Nations agenda to guide nations to achieve sustainability. To help nations reach the goals, we also need action from cities, businesses, and communities. The SDGs interact in complicated ways and sustainability assessment is used to understand the best ways to achieve them without too many negative

side-effects. We worked with a regional community in Australia to learn what sustainability means to them and what they believe they need to reach a sustainable future. We discovered that by working collaboratively with the people in the community to understand how their town works – looking at it from social, economic, and environmental perspectives – we learned much more about the important social factors in their community than if we hadn't worked with them. This is a positive outcome because these factors are often missed or left out in sustainability assessment. The assessment is more representative of how the community functions as a result. Overall we have a clearer understanding of the causes of problems in the local context, which means we can test different actions to fix those problems and help the town become more sustainable.

1 Introduction

Sustainable development is by nature an integrated, multidimensional endeavour. Typically, we codify the dimensions of sustainability to be environment, society, and economy, and the UN Sustainable Development Goals (SDGs) are built upon these dimensions (UN, 2015). Sustainable development demands the balancing of these dimensions such that meeting current human needs does not compromise the environment's capacity to meet the needs of future generations (The World Commission on Environment and Development, 1987), meaning that human-natural systems are strongly intertwined and cannot be decoupled (Folke et al., 2016). Beyond this we must also recognise that human-natural systems are diverse and multifaceted and there is no one-size-fits-all approach for achieving sustainable development (Moallemi et al., 2019). Representing human-natural systems for sustainability assessment requires tools that can support integration between interacting sectors, and cover multiple dimensions and scales. Additionally, it is now generally understood that societal transformation will be required to achieve a sustainable future (Leach et al., 2012; Bennett et al., 2019), and such transformation is best facilitated through knowledge co-production (Wyborn et al., 2019; Chambers et al., 2022).

Co-production refers to the way in which knowledge is collaboratively generated with a range of diverse participants and incorporating multiple knowledge systems. It is a process which is inherently political, as it requires the interaction of people who may all have differing perspectives upon the problem at hand (Forsyth, 2002). It is also something which should be approached with an understanding of power relations (Turnhout et al., 2020) and the positionality or perspective of participants (Holmes, 2020; Secules et al., 2021). Norström et al. (2020) proposed four principles for knowledge co-production: that it is context-based, pluralistic, goal-oriented, and interactive. The modes of co-production for sustainability have been explored with reference to how the process approaches problems, agency, and interacting with power, and the desired outcome of the process (Chambers et al., 2021). Bandola-Gill et al., (2022) examined the approaches taken by different disciplines, and a key conclusion from their work is that more inclusive forms of co-production seek to expand the boundary of who is considered a knowledge-producer. Fleming et al., (2023) defined three separate activities on the spectrum of co-production – co-design, co-development, and co-delivery. This delineation of activities assists with defining roles for co-production practice. Moallemi, de Haan, et al. (2021) developed a framework to encourage co-production practices in sustainability science, and Chambers et al. (2022) explored the variation in co-production for sustainability. These two papers explore the practical side of knowledge co-production for sustainability and examine the potential benefits and challenges, as well as the contexts in which co-production might be applied.

Sustainability assessment is used to assist with decision making, which evaluates whether sustainability actions are achieving their intended outcomes (Hacking and Guthrie, 2008). Approaches to sustainability assessment include multi-criteria analysis (Kain and Söderberg, 2008), indicators and indices, life cycle assessment, and integrated methods including conceptual modelling, systems modelling, and scenario modelling (Ness et al., 2007) which can incorporate complex interactions such as trade-offs, uncertainty, feedbacks, and pluralism (Bond et al., 2012). In the era of the SDGs, global and national *ex ante* sustainability assessment is often performed through integrated assessment modelling of scenarios (Allen et al., 2017; Soergel et al., 2021; Moallemi et al., 2022), although the models and scenarios currently used for this are not without their limitations (Soergel et al., 2021; Moallemi et al., 2022). These *ex ante* approaches are rarely used at the local scale for many reasons including the challenge of understanding heterogeneities on the ground (van Soest et al., 2019), the difficulty of customising complex models for local case studies (Verburg et al., 2016), and a (misguided) sense that the impact at the local scale is less of a concern (Easterling, 1997). One of the principal methods used by local governments to assess progress toward SDG achievement involves evaluation of existing policy against SDG indicators (e.g., City of Melbourne, 2022). This reduces the idea of sustainability achievement to a *post-hoc* box-ticking exercise and does not necessarily address planning *toward* the type of ambitious transformative change that will be required (Randers et al., 2019). Sustainability is a discipline which is defined by the interconnection of human-natural systems, and systems modelling is an approach which has the capability to explore this (Moallemi, Bertone, et al., 2021). There is an opportunity to extend these *ex ante* assessment approaches, such as systems mapping and modelling, to the local scale to expand the means by which sustainability can be assessed.

The transformative change needed to achieve the SDGs must occur at a global scale driven by national governments, however the action to achieve this change will happen at the local scale (Hajer et al., 2015; Bai et al., 2016; Moallemi et al., 2019; Tan et al., 2019). There are those who seek to counter this argument; who state that local and global sustainability cannot be achieved concurrently (Voinov and Farley, 2007), however other studies refute this position. Ostrom (2010; 2012) posits the role of polycentrism in global change and argues against delaying local action while we wait for global agreements to be reached. In China, regional sustainability initiatives improved sustainability both at the regional and national scales (Xu et al., 2020). Kanter et al., (2018) examined agricultural trade-offs in the context of the SDGs and concluded that decision contexts are intensely local and the choice of measurement indicator should reflect the spatial scale. An examination of SDG localisation in Europe and the UK found that localisation initiatives were occurring without regard for, or coordination by, government, and that as a result, monitoring and measurement was unlikely to occur by a formal process (Jones and Comfort, 2020). As with many discussions concerning sustainability there are a plurality of views and realities, and we acknowledge there is a danger that local sustainability can come at the expense of the sustainability of other regions. However this points to the need for greater effort in integrating sustainability within and between scales, rather than abandoning local sustainability (Liu, 2017; Purvis et al., 2021). The idea of local scale sustainability is also tightly linked to the motivations for co-production (Wyborn et al., 2019), with a desire for local context, pluralism, and participation.

We seek to link these three concepts: co-production, SDG assessment, and local scale. By using knowledge co-production, researchers and participants can develop a shared understanding of transformation required to achieve the SDGs at the local scale. Using Norström's (2020) four principles, we see co-production linked to SDG assessment and the local scale in the following ways:

- Context-based: to ensure local context is incorporated, localisation of the SDGs is key (Moallemi et al., 2019).
- Pluralistic: a collaboration between researchers and partners achieves pluralism, with the understanding that co-production partners represent a diversity of knowledge and expertise with intersectoral lived experience (Cooke et al., 2021; Zurba et al., 2021).
- Goal-oriented: to collaboratively find pathways to the SDGs through identifying and fostering local solutions for sustainability (Beck and Forsyth, 2020).
- Interactive: to encourage participation with a range of active engagements (Basco-Carrera et al., 2017; Voinov et al., 2018).

Then through an *ex ante* assessment via systems mapping (and eventually modelling), we can assess which solutions will allow progress to those goals. Transformative change consistent with local values should be the real purpose behind sustainability assessment and action to achieve the SDGs at the local scale.

In this paper, we describe our process of co-produced systems mapping for sustainability assessment with a local community of a regional town in southern Australia. As part of an iterative process of model development, we used participatory system mapping techniques with open participation for the community to describe their understanding of the interconnections between sectors. Because our work is grounded in the philosophy that sustainability is best achieved, and most likely to be successful, through participation of stakeholders who will be most affected by it, we used knowledge co-production to develop our understanding of the system. In line with the conclusion from Bandola-Gill et al., (2022) noted above, we expanded the definition of who was considered an *expert* to include all participants in our co-production engagements, with the justification that those with lived experience of the system were its expert knowledge holders. In this way, the development of the systems map was driven by the community, ensuring that we captured what mattered most to them. The purpose of the systems map is to inform the design of a systems model to assist with decision-making for local sustainability through quantifying pathways to achieve co-produced sustainability ambitions, framed by the SDGs. Here we describe our co-production approach and the methods that we used to co-develop the systems map. We discuss the implications of our results in the context of three research gaps that Moallemi, Bertone, et al. (2021) found in their review of systems modelling for the SDGs at the local scale: that 'societal' SDGs require greater consideration in modelling; stakeholder participation was infrequently reported in case studies; and community-level modelling has not been widely used. To conclude, we reflect on how our process of knowledge co-production aligns with the modes of co-production identified by Chambers et al. (2021) and with the forms of co-production expressed by Bandola-Gill et al. (2022), and the implications for sustainable development.

2 Methods

2.1 Understanding the case study

Our local case study is the town of Forrest, located in the Otways region of Victoria in south-eastern Australia. The Traditional Owners of the land are the Eastern Maar. At the 2021 census there was a population of 257 people, and the town is a post-logging community with some agricultural activity, in transition to tourism and potentially other sectors. Forrest is historically a low socioeconomic status community, and while that has improved in recent years with the reinvigoration of the local economy due to tourism, entrenched disadvantage persists (Colac Otway Shire, 2021: 17–18; S1). Forrest is located on the edge of the Great Otway National Park and straddles two different bioregions: the Otway Plain bioregion, characterised by grassy plains and open woodland; and the Otway Ranges bioregion, predominantly wet forest and temperate rainforest ecosystems (Figure 1). This proximity to the protected areas of the national park makes it a desirable location for tourism and for nature-loving residents, while the grassy plains make for suitable agricultural land. However, the nearby national park contributes to the area's very high bushfire risk profile.

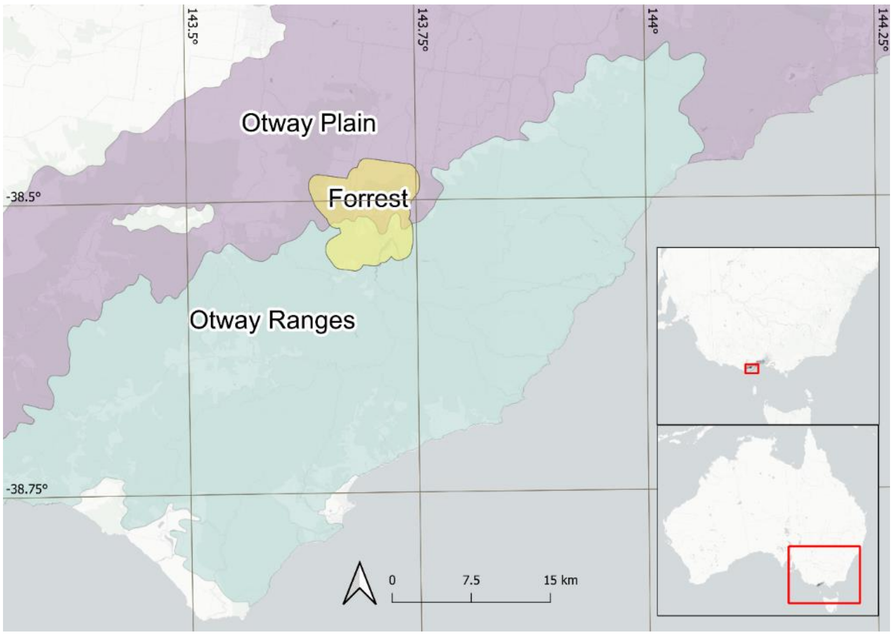

Figure 1: A map of the case study area. The two bioregions of Otway Plain and Otway Ranges are indicated in purple and green respectively. The township of Forrest is highlighted in yellow. There are two inset maps indicating the case study location in context of the state of Victoria (top) and the country of Australia (bottom).

2.1.1 Project background

The broad remit of the project of which this systems mapping study was a part was to find pathways to the SDGs at the local scale. University researchers partnered with those who live in the community of Forrest, auspiced by the Forrest and District Community Group (FDCG) who were seeking to improve the resilience of the township to climate change. The project was co-funded by a philanthropic organisation, the university, and FDCG, and the project proposal was co-designed by the latter two. The research team consisted of one principal investigator, two academic researchers, one practitioner (who is an expert in community engagement, with existing relationships with Forrest), and one member of the Forrest community (who liaised with FDCG).

Early in the project's inception, a participatory scenario modelling-based approach was decided upon by the academic partners to explore the pathways to the SDGs, for reasons outlined in section 1. We framed our research by identifying, with the community, which SDGs were important for the future of Forrest and finding locally specific actions that would help achieve those SDGs. The community chose the subset of local SDGs of greatest relevance to them through a combination of polling and facilitated discussion. Researchers contributed knowledge to SDG selection through a desktop review, but this did not substantially alter the choices made by the community. Community-identified actions for their sustainable future were synthesised into a community sustainability plan which was co-authored, contributed to, and reviewed by self-nominated community members (Szetey et al., 2020). The actions were embedded into a system dynamics model (Sterman, 2001) as levers for interventions that could be switched on or off, allowing model simulations to examine outcomes with and without interventions. The model itself was co-developed, based on local community knowledge, and it described the system of Forrest with multiple interacting sectors. The academic researcher partners created the quantitative model, however the community partners provided conceptual and qualitative systems mapping to support the quantitative model (as described in this paper). The model is intended to improve understanding of how actions will impact the functioning of the system, as well as whether the actions will achieve the desired outcomes of achieving the SDGs at the local scale. The work of the academic research partners contributed by quantifying the potential benefits and identifying trade-offs that might not have been foreseen. The boundary of the research was to define the potential actions and assess their ability to achieve sustainability at the local scale, rather than to see the actions through to implementation.

2.1.2 Knowledge co-production for sustainability

A widely used definition of sustainability comes from the Bruntland Report definition of sustainable development, which was expressed as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (The World Commission on Environment and Development, 1987: 42). In this definition, the Brundtland report authors represent that sustainable development requires the transformation of human systems (i.e., society and the economy) to satisfy human needs – with the eradication of inequality given priority – while not endangering natural systems that support us. The Sustainable Development Goals build on this definition by stimulating action for sustainable development for "people, planet, and prosperity", which are the alliterative equivalent to the three commonly accepted pillars of sustainability: society, environment, and economy, respectively (Purvis et al., 2019). We acknowledge the tension which exists within the sustainability community regarding various definitions and understandings of sustainability and sustainable development (Ruggerio, 2021) but for this study we used the framework of the SDGs at goal level (i.e., not targets or indicators), interpreted by the community.

Using the Co-3D framework (Fleming et al., 2023), this research project employed the first two stages of the framework, *co-design* (where the objectives, activities, and scope of the project were designed collaboratively), and *co-development* (where the activities and knowledge co-production is carried out). Further, we refer to *engagement activities* (or simply *activities)* in the following sections, which were structured events (boundary objects) where the research team engaged in co-production with the community, and *participants*, who were those who participated in the activities. In line with the observation by Bandola-Gill et al., (2022) that inclusiveness may be increased by expanding the boundary of those considered knowledge-producers, we defined those who lived in the township of Forrest to be our knowledge domain *experts.*

To understand the local context and learn what was important (and not important) for local sustainability in the case study, we undertook a range of engagement activities with the community

(Figure 2). We chose a set of participatory approaches using the framework developed by Moallemi, de Haan, et al. (2021). Implementing the framework found that with the requirements of the case study, *Open Space* (Martin et al., 2018) and *Facilitation* (Bohunovsky et al., 2011) methods would be the most suitable. Open Space refers to methods which bring people together in a facilitated manner to reach a shared understanding, and Facilitation is a similar approach but with greater structure, such as workshops. Our participatory methods were co-designed by two academic researchers, one practitioner who is an expert in community engagement, and one member of the Forrest community (who was born and raised in Forrest and is now raising a family there). Except for the events which were attended by invitation (the kitchen table discussion and semi-structured interviews), participation was open to anyone in the community, including children. The most recent census data indicates that 1.6% of Forrest's population self-describe as Indigenous, however we did not collect information regarding identity (of any sort) from participants. We advertised the activities through flyers posted in high traffic areas around the town, by word-of-mouth facilitated by the community-based researcher and members of the FDCG, on social media, and via the local newspaper.

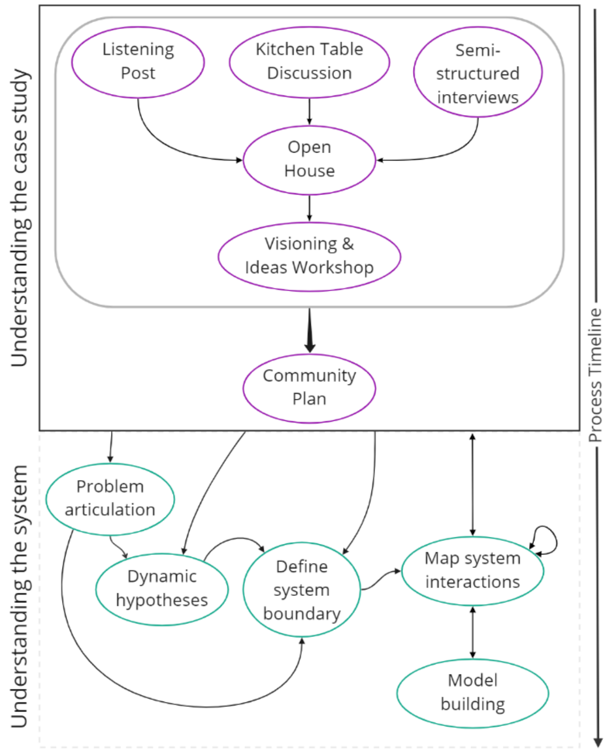

Figure 2: The process of co-production. Bidirectional arrows indicate iteration. The circular arrow on Map system interactions indicates that this was iterative. The arrow on the right indicates the timeline of activities.

The activities in Forrest intentionally began broadly, introducing the community to the SDGs at a superficial level (i.e., goal names) and discovering which of those were most important for Forrest – we called these *local SDGs*. Subsequent activities became more targeted, further eliciting details about what was important to the community with respect to each local SDG. These engagement activities have been discussed extensively in previous work (Szetey et al., 2021a; Szetey et al., 2021b), but we provide an overview of them below. We describe 'breaks' between the activities, which were intentionally planned as part of the sequence of engagement activities for two reasons. Firstly, the activities all built upon the preceding ones, so these breaks gave the research team an opportunity to consolidate what had been learned and incorporate this knowledge into the next activity. Secondly, we wanted to provide enough of a break for the participants to avoid participation fatigue but not forget what had occurred at the previous activity.

The research team met regularly before and after each activity to plan and reflect. As part of our initial planning sessions, we defined the project parameters (*negotiables* and *non-negotiables* for the research team); performed relationship mapping of other projects underway in Forrest at the time, and stakeholder mapping using an interest-influence matrix (Reed et al., 2009); and sketched out our preliminary engagement plan, nominating key statements and key questions for each stage. These statements and questions are noted in sequence below. This extensive range of engagement activities provided the research team with a good understanding of the issues, challenges, and boundary of the system, in Forrest.

The first three activities occurred at the same stage in the engagement sequence. The key statement for these activities was: “This is the SDG project.” The key question was “What are the topics of most relevance for Forrest?”

Listening Post: We had 55 participants in this activity, approximately one-fifth of the town’s population. This, our initial activity with the community, was an informal engagement in which we set up tables and a marquee beside the township’s general store on two mornings. The reasoning was to hold the activity in a location in which people would already be present rather than require participants to visit the researchers in a predefined location (Szetey et al., 2021a). Our purpose was to familiarise the community with the SDGs, which were displayed on posters, and understand what broad issues concerned them. We motivated this by asking “we would like to know what you think is important for the future of Forrest.” The research team engaged in conversation with any passers-by who stopped to enquire what we were doing; a useful strategy was for the community-based researcher (with established local relationships) to initiate conversation and then hand off to an academic partner to fill in details about the project. Additionally, we conducted a poll for participants to vote for the SDGs that they believed were most important to the future of their community. Each participant received three votes, and weighting was permitted so multiple votes could be allocated to one SDG. We also collected information via free-form text, either written on a board or contributed via one-on-one discussion with a researcher.

Kitchen Table Discussion: To understand a more nuanced and detailed view of community concerns, we conducted two facilitated Kitchen Table Discussions (van Hees et al., 2020) with community experts. The facilitator was the practitioner member of the research team. The eight participants for the first session were selected by a community-based researcher as having diverse experiences and included farmers, local business owners, and government employees. The second group consisted of seven members of the Forrest and District Community Group, the partnering organisation for the research project. There was no overlap in participants between the two groups to ensure a wide range of views from different members of the community. The participants were selected after the research team had mapped stakeholders and identified that there were a group of five influential residents in Forrest whose buy-in would be important for the research project to have impact in the community. These were included in the Kitchen Table Discussions, along with others selected by the community-based researcher. The discussion covered questions such as what the participants liked best about Forrest; what challenges and threats face the community; and how inequality affects Forrest.

Semi-structured interviews: To gain an understanding of how external stakeholders (i.e., not local residents) see community priorities, we interviewed three local government officials. The questions asked were intended to elicit in what capacity the officials worked with Forrest and its residents, what issues and challenges Forrest was facing now and into the future, and whether they felt our research project would need key actions to achieve its aims.

The key statements for the next activity were: “These are the themes”, “These are the SDGs of most interest”, and “These are the issues of concern”. The key questions were “What should the Forrest Plan look like?”, “How do the themes translate into a plan?”, “Who might drive the plan?” “How to resolve the dichotomies, e.g., development vs uniqueness, land prices vs holiday houses?”, and “Have we missed anything?”

Open House: There were 23 people registered as participating in this activity, which is 10% of the town’s population (some unregistered participants may have provided input but due to the nature of this event we were not able to capture that information). During a one-month break from the previous activities, we collated the information we had gathered into broad themes, such as *town character,* *housing, employment and economy, threats, infrastructure,* and *food security.* We created posters for each theme using local images and text quotes from the listening post and kitchen table discussion activities, and these were hung in the community hall over the course of two days where the residents could visit and provide feedback through conversation or in writing (DELWP, 2014). The timing of this activity was aligned with a community event already taking place in the town to maximise participation.

The key statements for the workshop was "This is what we've heard", and the key question was "What is the vision?"

Visioning and Ideas workshop: There were 16 participants at this workshop. After a further month's break following the Open House, we conducted a Visioning and Ideas workshop (Nam, 2013) to elicit a vision of a sustainable and thriving community. The facilitator (the practitioner researcher) verbally took the participants on a guided visualisation of a hypothetical walk through the town in 2030, and the participants imagined what changes they saw and wrote them down. These visions were then assembled into a mock newspaper template with participants working in groups, which were then shared with the larger group. The groups then discussed how they would achieve their vision and what tensions they could see that might inhibit that progress.

Community Plan development: During a period of extensive local pandemic lockdowns in 2020, the researchers synthesised all the information collected through the preceding activities, as well as additional engagement activities that the community had participated in over the preceding five years, into a community plan. These additional activities were not part of the study described here, but instead linked to local and state government projects (see Szetey et al., 2020). This plan detailed specific actions that the community had expressed as critical for town development (mainly infrastructure), as well as taking a snapshot of the state of community life in Forrest at the time. It also extended on the themes identified in the Open House and nominated ten key drivers of change, including *population and demographics, housing, inequality, local economy, transport and connectivity,* and *climate change.* The document underwent three rounds of expert review, twice by the community and once by non-resident stakeholders. The research team equated this expert review to the peer review process for academic research.

2.2 Understanding the system

2.2.1 Defining the system boundary

A co-produced output of these engagement activities was the definition of the system boundary, that is, the sectors within the community and township of Forrest which were of most concern to local residents. In particular, the key driving forces detailed in the community plan defined each system sector (e.g., population and demographics equated to the demographic sector; transport and connectivity to the transport and telecommunications sectors). This was the conceptual boundary for the system; the spatial boundary was limited to the township of Forrest; and the temporal boundary was specified as the time at which the system was examined (i.e., around 2020).

Having outlined this boundary, the research team developed our understanding of the sectors in greater detail using the method described by Sterman (2001) for *problem articulation* and constructing *dynamic hypotheses.* This process entails defining the problems that the community expressed throughout the engagement activities, and then constructing a hypothesis to explain how that problem arose and the contributing factors. This facilitates understanding of causal relationships of processes in the real world. Sterman (2001b) expressed that the hypotheses were considered “dynamic” because they are intended to describe the dynamics, or forces which induce change, of the problems. For many of the problems identified with our co-production partners, significant contribution was also made by them towards the formulation of the hypotheses. For example, housing availability and affordability was identified as a problem, and tourism was hypothesised to be a contributing factor to the issue of housing supply and high house prices. However this was not the only factor so an emerging understanding of the system on the part of the researchers was able to extend and link the local knowledge provided by the community in a collaborative manner, which enhanced the overall result.

2.2.2 Mapping system interactions

To improve the understanding of the system through co-production, we conducted a participatory systems mapping workshop (Sedlacko et al., 2014) in which the participants could design and define the interconnections between the system sectors. Unlike Sedlacko's et al., (2014) work, ours was not intended to map the system using causal loop diagrams, but instead elicit the ways in which the different sectors of the system interacted. The purpose underlying this strategy was to explore how interconnections can identified and mapped, considering the emphasis on interactions between different SDGs in research (Alcamo et al., 2020; Anderson et al., 2021; Bandari et al., 2021), and in light of the finding by Moallemi, Bertone, et al., (2021) that there are few published examples examining SDG interactions in systems modelling.

In the workshop, we introduced the participants to the idea of a system, how parts of a system are connected, and how perturbations in one part of a system can have spillover effects into other parts. We explained to them the conceptualisation of Forrest as a system and invited them to consider how the different sectors of the Forrest system interact with each other. To facilitate this process, we displayed large posters, one for each sector of the Forrest system. The posters had the name of the sector of interest in the centre, with all the other sectors surrounding it radially around the edge of the poster, connected to the centre with lines. The participants were asked to write along the connecting lines with a short explanation of how they felt those sectors were connected. The workshop design details are available in the Supporting Information (S2). The co-produced system interconnections described in the workshop were used to improve researcher understanding of the system.

The sector interconnections described by participants in the workshop were used to help develop the system model by progressing the draft model created by the academic researchers, or alternatively incorporating new structures. One new addition was the *cultural burning* structure, which refers to a practice that may require explanation for those unfamiliar with Australian Indigenous land management. Pre-colonisation, the Australian landscape was extensively managed by Indigenous peoples using cultural burning practices (Gott, 2005; Gammage, 2011; Pascoe, 2014). Cultural burning encompasses the use of fire management for many purposes, not limited to hazard reduction, hunting, and ceremonial (Fletcher et al., 2021). However, it is also part of a holistic practice known as 'caring for Country' which can be considered analogous to western ideas of planetary health (Horton and Lo, 2015; Yunkaporta, 2019; Steffensen, 2020). This was represented in our system mapping session as "healthy Country ↔ healthy people". We included *cultural burning* within the model in response to several factors identified by the participants, including a greater desire for Indigenous cultural connection and planetary health ideas, and its impact extends through the *Biodiversity* and *Health and Wellbeing* sectors of the system. Over the longer term, cultural burning would have a significant impact on bushfire risk, however this was challenging to represent as there is currently no quantitative knowledge of this effect; western science is still in the early stages of understanding Indigenous fire management (Fletcher et al., 2021).

3 Results

3.1 Systems understanding

Community engagement activities (section 2.1.2) identified six local SDGs for sustainability: SDG 3 Good health and wellbeing; SDG 6 Clean water and sanitation; SDG 8 Decent work and economic growth; SDG 11 Sustainable cities and communities; SDG 13 Climate action; and SDG 15 Life on land. The key driving forces defined in the community plan were: population and demographics; residential land development; affordability of property and suitability of housing; inequality; local economy; environment; major infrastructure projects; transport and connectivity; local school; and climate change. We synthesised the local SDGs and driving forces and this resulted in 12 sectors which delineated the system conceptual boundary: *Demography, Land Use, Housing, Economy, Tourism, Biodiversity, Climate change, Inequality, Health and wellbeing, Telecommunications, Infrastructure,* and *Transport.* This was almost a one-to-one mapping of the key driving forces; except that 'local school' was incorporated into the *Demographic* sector, 'transport and connectivity' were split into separate sectors ('connectivity' referring to telecommunications), and *Health and* *wellbeing* was established as a separate sector because of SDG 3. SDG 6 and 11 were represented across multiple sectors: SDG 6 in *Housing, Health and wellbeing* and *Infrastructure;* SDG 11 in *Demographic, Land Use, Economy, Housing, Transport, Tourism, Climate change, Infrastructure,* and *Inequality*.

With the wide range of sectors, there is an analogous range of sectoral problems including: an ageing population; increasing house prices; tension between tourism, housing, and the local economy; lack of wastewater infrastructure restricting new development; local biodiversity at risk from climate change; intergenerational inequality; lack of access to healthcare; poor internet; and insufficient regular public transport. Table 1 summarises the dynamic hypotheses for each sector. The full list of problem articulations and their dynamic hypotheses are provided in the Supporting Information (S3). We provide an illustrative example of a problem and hypothesis from the *Housing* sector here:

> *Problem:* Colac Otway Shire have designated that Forrest remain a low growth community and estimated a release of 3.5 permits per year for residential land development. There has only been one permit issued per year since 2011, so development has been below expected levels. There is scope for greater development in the future.
>
> *Hypothesis:* Building permits are not being granted by Council because potential developments cannot meet septic tank regulations. New wastewater infrastructure is required before any significant development may occur.

Table 1: The dynamic hypotheses for each sector in the local SDGs systems model

SECTOR	DYNAMIC HYPOTHESIS
Demographic	Ageing population due to in-migration of couples without children, and out-migration of young people. Population limited by housing availability and reduced job diversity.
	Closure of the primary school would end visitation from people outside the township (transporting children) who may then patronise local businesses.
Land use	Regenerative agriculture limits fertiliser use, which reduces nutrient runoff into waterways, improving local water quality and environment. It also boosts agricultural profits.
	Residents want laws restricting building on agricultural land relaxed, which may increase land transfer between agriculture and housing. An increase in agricultural business may increase land transfer between bush and agriculture.
Housing	Lack of housing development due to wastewater issues is constraining the housing and tourism accommodation supply. This increases house prices.
	New social housing may relieve rent stress caused by high house prices.
Economy	Tension between tourism, housing, and the economy. Residents resent tourism for its housing supply and price impacts, but benefit from its positive economic impact. New wastewater, enabling housing development, would ease this tension.
	Climate change will have a diminishing effect on agricultural profit in the long term. Land fertility may combat this, especially through regenerative agriculture.
	Local small businesses are dominated by tourism/ hospitality and farming. Other sectors are constrained by a lack of housing and office space, and poor internet.
Tourism	Tourist numbers are affected by the incidence of bushfire either locally or elsewhere in Victoria, by flooding, and by the quality of local infrastructure.
	Lack of wastewater infrastructure impedes the development of housing and tourism accommodation, thus constraining tourist numbers.

	An increase in bus frequency would enable growth in tourist numbers.
Biodiversity	Climate change and land-use change increase bushfire risk and land use change reduces biodiversity habitat. Indigenous cultural burning may mitigate biodiversity loss but has a significant lead-in/preparation time.
Climate change	The community is vulnerable to increasing bushfire, drought, and flooding. Negative effect of climate change on biodiversity may affect the eco-tourism economy. More frequent heatwaves will put older people at risk.
Inequality	Factors contributing are intergenerational inequality, income inequality, housing stress, employment, social gradient of health, travel inequality, and internet access.
Health and wellbeing	People experiencing income inequality have poorer health outcomes (social gradient of health). Living in regional areas impacts life expectancy. Building new wastewater infrastructure will reduce disease burden. The local environment has a positive effect on wellbeing but there is a trade-off from bushfire risk.
Telecomm-unications	Improved internet access would encourage new businesses which rely on connectivity, and better support existing residents and businesses. It is also necessary for education and health outcomes.
Infra-structure	Ageing septic systems don’t meet safety standards and new infrastructure is required. This affects the local environment and biodiversity, the local economy, health of residents, and additional development in the town. Upgrades to the Mountain bike trail network would encourage greater visitation. Issues remain around accommodation (i.e. housing supply) and wastewater. A Bushfire Place of Last Resort would have a positive impact on community health and wellbeing in the event of a bushfire and potentially prevent loss of life.
Transport	Road deaths on rural roads far exceed those in metropolitan areas.

Poor bus services restricts mobility for those on lower incomes and those unable to drive, due to age or disability. More tourists may visit if there was better public transport access.

The understanding of each sector developed from the problems and dynamic hypotheses was mapped into a series of independent systems maps by the research team. All these systems maps are provided in the Supporting Information (S4), but one example is provided here for the *Housing* sector (Figure 3). The arrows indicate flows through the sector however this representation is not a flowchart; the arrows do not *require* that there is movement, but only show the direction of influence. In Figure 3, housing supply is split into tourism housing and residential housing, and a hypothetical social housing stock. The presence of wastewater infrastructure and the availability of land are the influential factors on whether new housing can be constructed, thus increasing the housing supply. Population impacts whether there is enough residential housing; tourist numbers impact whether there is enough tourism housing; and there is transfer between tourism and residential housing (which, at the current time, is one-way). The cost of housing, influenced by the housing supply, impacts whether housing stress is experienced by residents, and the presence of social housing may relieve housing stress.

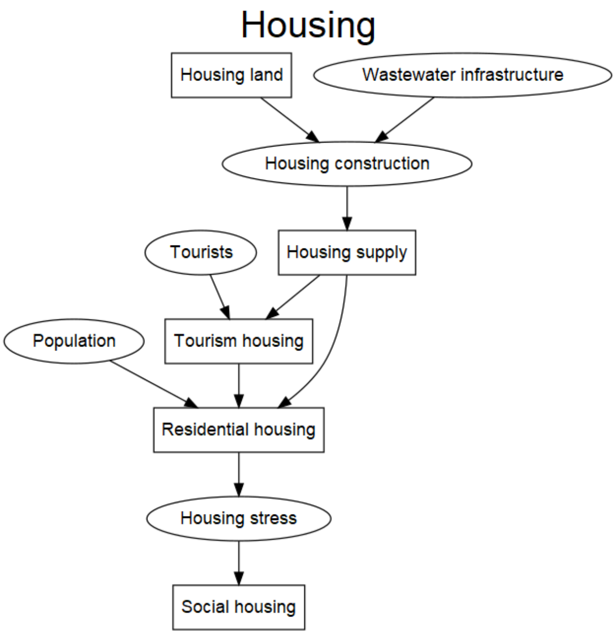

Figure 3: Systems map of the *Housing* sector, indicating endogenous flows through the sector and inward exogenous intersectoral influences (but not outward exogenous intersectoral flows). The boxes in the conceptual model indicate stock variables (in system dynamics terms), the ovals represent pressures on those stocks.

3.2 Systems mapping workshop

We had 22 participants at the systems mapping workshop. A representative of the Eastern Maar attended the workshop to speak for the views of the local Indigenous corporation. This activity produced a rich dataset of responses which went beyond simply defining the interconnections between sectors. We have provided the complete set of completed workshop posters in the Supporting Information (S5), but here we show one example (Figure 4) to demonstrate the results obtained, and have summarised the responses for another example (Table 2). Examples of novel insights from the systems map included representing cultural burning in the *Climate change* sector (see section 2.2.2), satisfying the community's desire, and as a proxy, for Indigenous land management and greater cultural connection; social housing, which does not currently exist in Forrest but can be imagined as an option for sustainability pathways; and understanding the role that improved public transport could play in Forrest (which we referred to as *travel equity* – ensuring that all residents have access to equitable, reliable, and frequent transport options). The housing sector is an example of a sector which received extensive reconsideration after the system mapping workshop, as prior to the workshop housing stress and social housing was not part of the systems map or conceptual model.

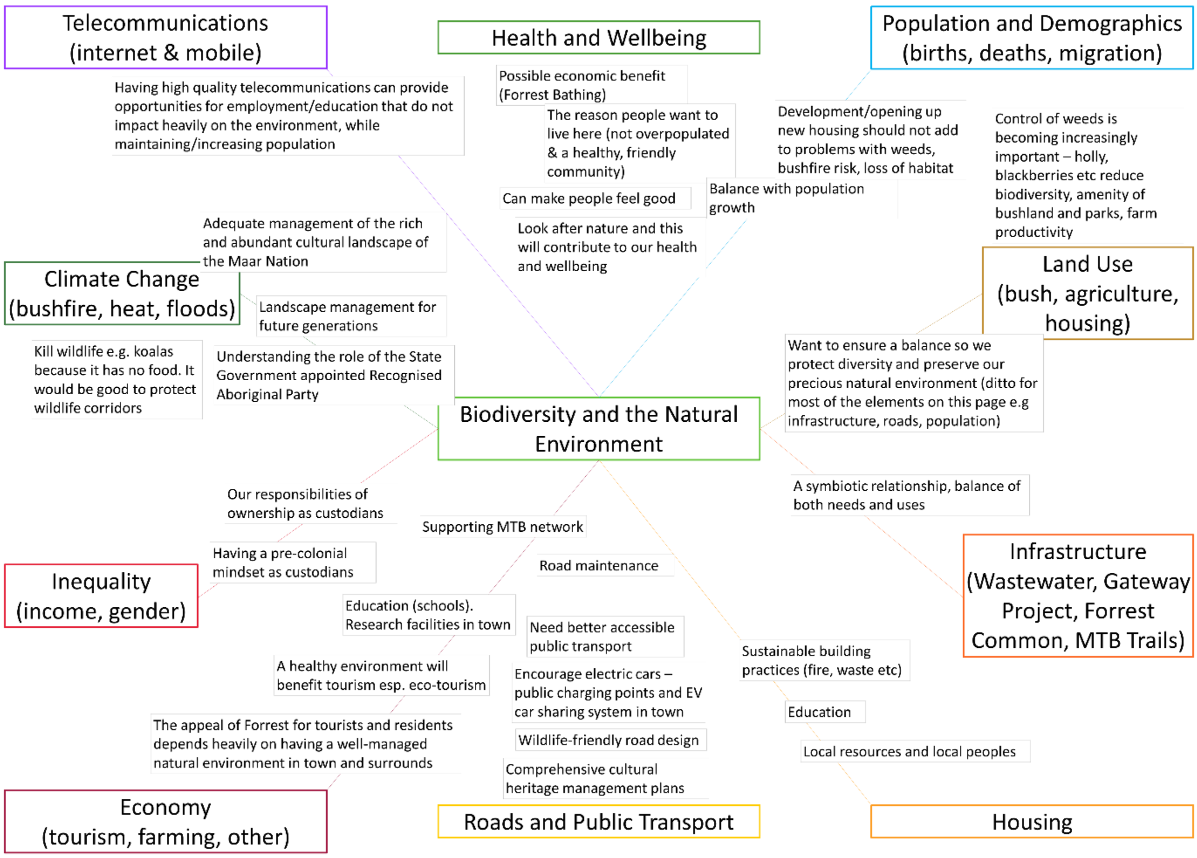

Figure 4: One example of a transcribed completed poster from the systems mapping workshop. The poster shows the community understanding of the interaction of the biodiversity sector (centre) with the other sectors.

Table 2: A summary of workshop participant responses to the interconnection between inequality and the other sectors in Forrest.

Sectors that interact with inequality	Nature of the interaction
Telecommunications	People experiencing income inequality can’t afford the internet or a phone.
	Key information cannot be shared when access to communications is unequal.
Climate change	People experiencing inequality will be more affected by climate change and its negative impacts.
Biodiversity	Traditional Owners can’t afford to live in Forrest, impacting the community’s ability to incorporate Traditional Owner knowledge.
	The dispossession of First Nations peoples and the change to landscape resulted in negative impact to Country wellbeing.
Economy	Community/government should enable those on low incomes with mentoring, finance, education.
Health & wellbeing	Embedded inequality, stigma, and discrimination results in poor health outcomes.
	People experiencing inequality have poorer health outcomes.
	Understanding Forrest’s intergenerational inequality is important for developing solutions for health and wellbeing.
Transport	Many groups need access to good public transport (young, old, low-income, disabled, without licence, etc).
	Electric vehicle car share could provide low-cost transport.
Demographics	Diversity of population across income levels should be encouraged.
	Vacant possession of housing brings about inequality.
Land use	Social housing option could assist with controlling tourism, housing conversion and housing prices.
Infrastructure	Costing of wastewater solutions will affect rich and poor households differently.

	New infrastructure will increase job diversity and improve wealth distribution.
Housing	Those of lower income cannot afford to live in Forrest due to high housing costs, reducing population income diversity and lowering community cohesion.

3.3 Key system interactions

Figure 5 shows the sectors of the system, broadly describes what each sector comprises, shows interactions between sectors, and identifies the local SDGs relevant to each. There are many interconnections between the system sectors, represented in Figure 5 by linking arrows. For example, there are six 'outgoing' connections for the model sector *Climate change,* and five for the sectors *Housing, Economy,* and *Population,* indicating that these sectors have the broadest impact on other model sectors. These connections can be either synergies or trade-offs. For example, 'climate impact on tourism/agriculture' and 'flood damage to roads' are trade-offs, while 'cultural burning impact' is a synergy. Conversely, *Inequality* has five 'incoming' connections, and *Health and Wellbeing, Tourism, Economy,* and *Housing* have four, signifying that these are the model sectors which are most impacted by other sectors. Characterising these interconnections helps to gain understanding of any counterintuitive behaviour (especially cross-sectoral) that may have occurred in the system and to identify levers for interventions.

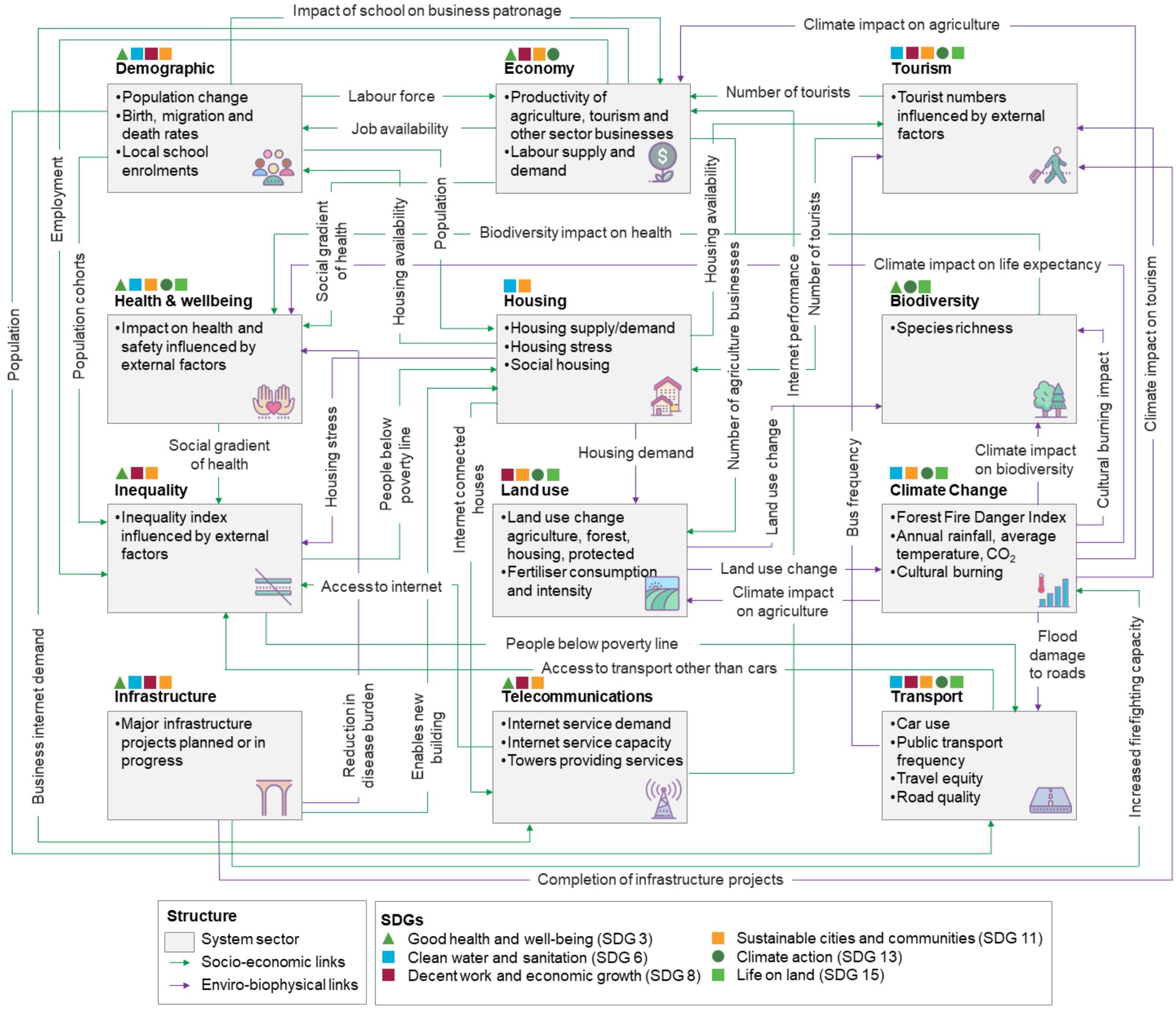

Figure 5: The interactions between the twelve system sectors (visualisation inspired by Figure 2 in Moallemi, Gao, et al. (2022)).

At a deeper level, we can isolate some of the cross-sectoral interconnections and identify where feedback interactions occur. In Figure 6, we have selected five key feedback interactions that play an important role in the Forrest system (these are not the only feedback interactions present in the system, important or otherwise). These interactions are explained as follows:

- **The telecommunications-economy interaction (a)** demonstrates how effective internet services are needed for a healthy economy, which will then affect the number of local jobs available, which has an impact on the local population, who in turn put pressure on internet services.

- **The inequality-housing interaction (b)** represents how housing stress caused by rising house prices leads to rising inequality. This inequality means an increasing proportion of the population will be below the poverty line, which leads to demand for social housing. The availability of housing has an impact on the population of the town, the disaggregation of which identifies many of the key determinants of inequality.
- **The land use-climate change-economy interaction (c)** shows how land-use change is a factor in climate change, how the impact of climate change on agriculture affects both the economy and future land use, leading to an effect on the number of agricultural businesses, again impacting land use.
- **The tourism-housing-economy interaction (d)** represents the complex interactions of tourism and housing, where (since tourism and residential housing come from the same housing stock, which is limited) housing availability affects both the population of Forrest and the number of tourists which can visit; but the population also impacts the number of people resident in Forrest who can be part of the labour force – which in turn has an effect on the number of tourists as staff are required for the service economy.
- **The climate change-biodiversity-health and wellbeing interaction (e)** does not present a feedback interaction as the arrows do not loop back to climate change, but instead shows how climate change is a *pressure*. It has (generally negative) effects on both biodiversity and health and wellbeing, but as part of the climate change sector, cultural burning's impact on the health of Country affects biodiversity, which in turn affects health and wellbeing.

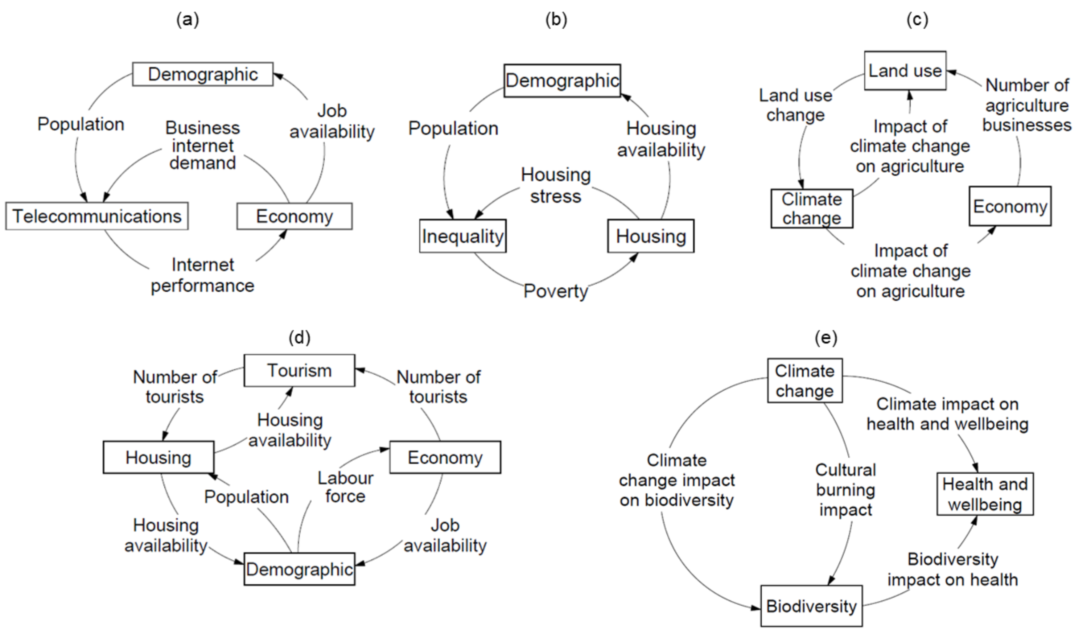

Figure 6: Five cross-sectoral feedback interactions. (a) telecommunications-economy; (b) inequality-housing; (c) land use-climate change-economy; (d) tourism-economy-housing; (e) climate change-biodiversity-health and wellbeing. These represent the flows across sectors in the system similar to Figure 5, but isolated to exhibit the interlinked influences across the system.

This final interaction (e) is reflected in the *Climate change* sector (Figure 5) where most of the connections are outward. This tendency of one sector to have substantial influence over other sectors is even more pronounced with the *Infrastructure* sector, which exclusively has outward connections. This does not mean that there are no inward influences on these sectors in the system, but rather that these are less material. We discuss this further in section 4.2.

4 Discussion

In this research, we used knowledge co-production to develop a systems map to understand interactions between societal, economic, and environmental priorities in the context of a local community, for the purpose of sustainability assessment. There were two aspects to this co-production: the initial scoping, information elicitation, and goal-setting phase (Szetey et al., 2021a);

and the systems mapping which will be used to inform the design of a systems model in the future. We focused on the gaps identified by Moallemi, Bertone, et al. (2021), namely the conceptualisation of societal factors, stakeholder participation, and greater attention to the interconnections between sectors. The final systems map contains many interconnections that we learned about exclusively through the co-production process. We consider this to be a direct result of the collaboration between researchers and the community of Forrest and the co-design and co-development process we employed.

4.1 Mapping social elements

The local SDGs identified in collaboration with the community (section 3.1) included the societal SDGs *Good health and wellbeing* (SDG 3) and *Sustainable cities and communities* (SDG 11). We included system sectors representing societal elements of demography (i.e., human population dynamics), housing, health and wellbeing, inequality, telecommunications (a socio-technical sector representing how humans interact with telecommunications), and transport (a sector which includes travel equity). We represented these societal elements endogenously within the systems map, as these are key factors underpinning societal transformation and SDG achievement. As discussed by Trutnevyte et al. (2019), if societal factors like these are not directly included in multisectoral modelling, any policy recommendations or conclusions drawn from the model results may be biased toward technological or easily quantifiable actions. However, the co-production process revealed a much richer narrative around the social aspects of sustainability.

The environmental and economic sectors of sustainability are, in general, easier to measure quantitatively than the social and are thus perhaps more generalisable across case studies, inasmuch as biophysical and economic indicators are usually considered objective, while social indictors tend to be more subjective – these various indicators and their use in both SDG monitoring and wellbeing measurement is an active area of scholarship (e.g., Costanza et al., 2016; Cook and Davíðsdóttir, 2021; Cook et al., 2023). However, we found considerable nuance in the social aspects that we could only learn via a co-production process, and with researcher openness to elements outside their disciplinary expertise. Knowledge co-production teased out much more detail around social issues in areas that may not have initially seemed to have a social focus. For example, when we originally designed the *Transport* sector, it was not conceived as a social equity problem (although, in line with the above observation regarding external disciplines, critical regional geography does understand transport in this way (Goetz et al., 2009)). However, the lack of regular public transport to Forrest creates several inequitable outcomes: from unequal access to transport between those with and without cars (even those with cars may not be able to afford fuel); further, lack of access to cars might be age or disability related, thus creating an intersectional equity issue, where access to transport is lacking *and* there is an additional equity layer. This was elicited through knowledge co-production, with comments such as “Many groups need access to good public transport (young, old, low-income, disabled, without licence, etc)”, “Accessible transport to Colac [major town] imperative (food/health/medical)”, “How do we provide access/transport for older people”, and “Support for older/poorer/younger people without cars is needed with better public transport” (Table 2; S3). Indeed, the co-production process drew out far more social interconnections between system sectors than any other type of interaction, a finding that is supported by Beaudoin et al. (2022).

More generally, we suggest that researchers should consider more deeply the opportunities that exist to examine social elements in systems in order to strengthen sustainability outcomes. A framework such as the SDGs already includes aspects of social sustainability and so its use is an excellent starting point from which to examine social elements. Through knowledge co-production, a conceptual understanding of the important social elements of the system can then be elaborated upon. It was our experience that participants had an intuitive understanding of systems interconnections and thus were fully capable of mapping out causal drivers for the identified problems in the system, which may not be the case for all types of human-natural systems mapping and modelling. Further, the use of co-production itself leads to greater capacity for exploring social elements, as the local-scale knowledge holders innately examined local problems through a social lens.

4.2 Mapping interconnections

Understanding the interconnections between system sectors provides a gauge for knowing where to place interventions for the greatest effect. It is clear from Figure 5 Figure 5: The interactions between the twelve system sectors (visualisation inspired by Figure 2 in Moallemi, Gao, et al. (2022)).that *Climate change* is one of the system sectors with the greatest outward interconnection. While climate change is an area with which the local scale is typically not involved – although this may be due to factors unrelated to the scale, such as funding (Messori et al., 2020), insufficient policy (Armstrong, 2022), or governance (Dupuits and Cronkleton, 2020) – more can be achieved on climate adaptation and this is evident within the systems map. For example, cultural burning (Fletcher et al., 2021) satisfied community desire for greater Indigenous connection as well as improving biodiversity and the economy by reducing catastrophic bushfire risk (Abram et al., 2021). Conversely, *Inequality* has the greatest number of incoming interconnections on the systems map, implying that inequality is a multifaceted and complex problem. *Inequality* has many inputs from other sectors, including accepted contributors to inequality, such as unemployment (from *Economy*), poverty, and disability, but the co-production process highlighted additional factors such as travel inequality (from *Transport*), housing stress (from *Housing*), and intergenerational inequality (from *Demographics*).

We heard from participants that one of the greatest advantages for living in Forrest was the pristine natural environment (SDG 15, the *Biodiversity* model sector), which had positive benefits to physical and mental health (SDG 3, *Health and wellbeing*), and they wanted to be sure that any economic progress (SDG 8, *Economy* and *Tourism*) did not impact negatively on the environment. Coupled with these concerns were the effect on the housing market from tourism accommodation (SDG 11, *Housing*) and the restriction on new housing development caused by the lack of wastewater infrastructure (SDG 6, *Infrastructure*). Hence, interconnections between system sectors are often indirect and this is made explicit in the feedback loops in Figure 6. This is one of the great strengths of systems mapping and modelling, uniquely enabling the comprehensive representation of complex coupled human-natural systems which is critical to avoid unintended consequences of policy interventions. There are multisectoral interactions missing from current models (Calvin and Bond-Lamberty, 2018; van Vuuren et al., 2012) and our findings suggest that knowledge co-production can go a long way towards filling these gaps at least at the local scale.

In the context of the SDGs, these interconnections can also be characterised as synergies and trade-offs. In the example described above, SDG 15 has synergies with SDG 3 but trade-offs with SDG 8. SDG 11 has trade-offs with SDG 8 but synergies with SDG 6. The co-production process aided in the identification of these synergies and trade-offs with the detailed explanations provided by participants of the way in which the system sectors were interconnected. Table 2 provides examples such as inequality resulting in poor health outcomes (synergy SDG 3-10, where reducing inequality improves health outcomes), dispossession of Indigenous peoples from their land leading to land management practices which do not support biodiversity (synergy SDG 10-15, where reducing inequality of Traditional Owners and engaging them to 'heal Country' will improve biodiversity). Trade-offs are most often seen between SDG 8 and SDG 15, which manifests as the tension between tourism and environmental impact in this case study. This illustrates one of the struggles of the SDGs and sustainable development more generally, which is that economic development is often seen to be at odds with environmental goals, but is required to support many social goals (although this interpretation is contentious, and many other scholars hold that economic growth is not needed (Sandberg et al., 2019; D'Alessandro et al., 2020))

Bringing a systems understanding through mapping to multisectoral modelling is key to correctly characterising interconnections, whether the modelling approach is system dynamics or something else. van Vuuren et al. (2012) recognised this as 'information exchange', and Moallemi, Gao, et al. (2022) refer to it as 'sectoral dynamics', but it is the awareness that human-natural systems are complex and have many underlying drivers that may be outside of the scope of the system being modelled, if that systems understanding is not sufficiently incorporated into the model design. Researcher openness to learning via knowledge co-production, iterative development, and cross-sectoral scope is required to enable the systems understanding and suitable representation of interconnections.

4.3 Co-production in practice

Through the process of knowledge co-production, we as researchers cast the community as knowledge domain experts. We did not explicitly examine questions of power, however we did engage with the different levels of agency in the community when we undertook stakeholder and interest-influence mapping, identifying that there were five key community members. But our specific engagement with these key people only occurred in the kitchen table discussion, motivated by the hope that it would encourage wider participation in other activities. Feedback received from kitchen table discussion participants indicated that the activity made them feel more “at ease” with the SDG project in the community. We hope that our work has granted the community greater agency to advocate for their identified sustainability actions, but it is not yet clear if that has been the outcome as no evaluation process was conducted. For the systems mapping, we integrated the community’s knowledge with our modelling expertise, which will be used to co-develop the systems model. We see this as contributing to the categories of knowledge co-production that Bandola-Gill et al., (2022) describe through their literature review as *knowledge democracy* and *transdisciplinarity* as we were integrating different knowledge systems and incorporating knowledge from a variety of actors. Further, using the Chambers et al. (2021) modes of co-production, we clearly engaged with *researching solutions*, as one of our goals was to identify community-derived actions to achieve sustainability, and that also led us to *empowering voices* from working solely with local actors. If we consider the modes of co-production as a spectrum, to a lesser extent we engaged with *navigating differences* (differences in values between participants) and *reframing agency*: we endeavoured to frame community knowledge as dominant, with researchers providing the expertise to shape it into the final systems map. Some conflicting views were exposed, however open discussion generally facilitated consensus and enabled resolution. One example of this occurred when an article was published in the local newspaper describing the systems mapping workshop and its results; the article did not describe the purpose of the results sufficiently – which was to explore options for achieving a sustainable future – and spurred one resident to email expressing concern that some of the options described in the article were being implemented without sufficient community consultation, as they did not want some of those options. The systems mapping workshop and its results provided an example of reframing agency, whereby the participants expressed their own understanding of the sectoral interconnections of the Forrest system, which led to the finding by researchers that many of the participants viewed these interconnections with a social lens (as opposed to environmental or economic). Additionally, earlier in the co-production process where the local SDGs were identified, the definition of each SDG was kept deliberately high-level, with only the goal names used. This allowed the participants to develop their own locally relevant interpretation of what the SDGs meant, for example, SDG 8 Decent work and economic growth was interpreted locally as "A sustainable and diverse economy" (this reframing of the SDGs occurred explicitly as part of the community plan process, and is described in Szetey et al., (2021b))

Critically, understanding the purpose of the co-production work also allowed us to identify and plan for risks and opportunities as explored in Chambers et al. (2021). Our work provides a foundation for advocating for policy change and addressing local needs (through articulating defined goals) and capacity building in terms of systems thinking literacy and deliberate consideration of transformation in the community. However, although we endeavoured to capture a diverse range of knowledge from the community, there are likely omissions. For example, while there were strong voices advocating for those of lower socioeconomic status, we suspect that few lower socioeconomic status residents actually participated. We also understand that because of this, the dominant framing of sustainable futures may not be fully inclusive and may risk an 'echo-chamber' effect that reinforced that dominant voice (Chambers et al., 2021). We sought to avoid this outcome as much as possible; our community collaborators encouraged participation from all socioeconomic levels of the community to ensure a broad a range of views, but despite this, the systems mapping workshop only included 8.5% of the township's population as participants. However, we intend that the model results based on the systems mapping will demonstrate a range of options for sustainability outcomes and it is then the community's decision (as a collective) to decide whether to proceed further. The model will include a range of options identified through the co-production process which can demonstrate the benefits and trade-offs to support decision making. Hard choices will need to be made as it is unlikely every action will be able to be funded and implemented.

While co-production is important and enabled many of our central findings, it must also be employed with care. Mochizuki and Wada (2022) discuss the need for including reflexivity in the *ex ante* methods of assessment that incorporate knowledge co-production. Reflection of the process is essential not only for ethical reasons (West and Schill, 2022), but also for the model-building journey (Zare et al., 2020). Our reflection identified strengths in the co-production process such as the empowerment of community voices and inclusion of local community knowledge, but also potential weaknesses with respect to inclusivity of the process. Co-production approaches can help render many hidden processes of modelling transparent (for example, with the systems mapping described in this work), as well as challenge previously known or hidden assumptions on the dynamics of the system (Sedlacko et al., 2014; Eker et al., 2018). Critical reflection on the strengths and weaknesses of what a model can offer, as well as engagement processes, and sharing these with the community, supports relationship and trust building with local knowledge holders. As local knowledge holders are increasingly sought to contribute to the co-production of models, especially for greater incorporation of social aspects of sustainability, adequate time must be devoted to reflective practices as part of the co-production research process.

We acknowledge that in this paper we have frequently referred to the systems mapping activity (which is ostensibly the focus of this study) as being 'part of the sustainability assessment process' or 'part of the co-production process,' meanwhile describing other parts of the process which are not systems mapping. This also includes future work such as model development, which may at times have been mentioned in this manuscript as if it had already been completed. This is principally due to the nature of both co-production processes and sustainability research, which is often messy, iterative, and overlapping (Zare et al., 2020). Figure 2 appears to lay out a neat timeline of events, and the section “Understanding the Case Study” was chiefly quite ordered. However the section “Understanding the System” was less so, and the bleed-through of different activities may be apparent from some of the descriptions provided here. Rather than minimise this apparent confusion, we think it is worth highlighting that co-production processes may proceed haphazardly and that this should be normalised, as it provides a learning environment for all involved (Chambers et al., 2022).

Understanding the nuances of co-production and its many aspects can be challenging, but the benefit exists in the more balanced and representative knowledge that it provides. As a researcher, it is worthwhile to explore recent scholarship on knowledge co-production such as the comprehensive review by Wyborn et al. (2019); Norström’s et al. (2020) examination of co-production in sustainability; Chamber’s et al. (2021) definition of modes of co-production; and the primer of “What is co-production…” (Bandola-Gill et al., 2022). Many of these papers deliver existing frameworks and processes, and so provide detailed methods to improve the practice of knowledge co-production. By understanding many of the fundamentals of co-production discussed by these authors, researchers can bring those principles to bear in designing and examining their work through reflection and informed consideration.

4.4 Future work

This paper describes the participatory systems mapping process, as part of a larger local-scale sustainability assessment co-production project with the community in Forrest. Future work will demonstrate a system dynamics model that will be based upon the systems mapping, the model’s application, and analyse scenarios to find locally-specific pathways to sustainability. In previous work we co-developed scenarios with the community of Forrest (Szetey et al., 2021a), and the next step once the model is completed will be to simulate those scenarios to understand possible futures. The co-developed systems map identified several clear intervention points to be built into the model, such as the building of infrastructure (particularly wastewater), increasing bus services, enabling social housing, introducing cultural burning, and allowing new telecommunications towers to be built. There are additional levers which can be modelled, including but not limited to changing minimum housing lot size, modifying inflationary rates, varying the fraction of land which is farmed regeneratively, and allowing for buses to transport tourists.

5 Conclusion

This work explored a co-produced participatory systems mapping process as part of a larger project undertaking *ex ante* sustainability assessment for the SDGs at the local scale. As part of the co-production process, we asked the community to focus on the interconnections between sectors in the systems, and this resulted in a better understanding of where potential interventions may exist to enable transformation to a more sustainable community. These sectoral interconnections are often missing from other types of multisectoral models, thus it seems that understanding them may be a key research focus for sustainability assessment using models. We reiterate here that the co-production process facilitated this understanding and we believe that engaging with stakeholders, at all scales, is invaluable. The second key insight that we observed was the way in which the co-production process highlighted social issues over economic or environmental ones. This makes sense in hindsight, as people will typically focus on the human element in human-natural systems. This is a timely insight for human-natural systems modelling, as environmental systems representations have been well explored in literature and practice, while social-based ones have lagged behind. Given the emerging attention on modelling social factors from both the sustainability and modelling communities, we found using a knowledge co-design/co-development approach to inform model development assisted in achieving this goal. Social issues tend to be localised, which is one reason why local-scale sustainability assessment is important, as many of the social issues elicited through the engagement process were unknown to the researchers and were not predictable through top-down processes. The contribution of this work lies in the employment of *ex ante* sustainability assessment methods to a local-scale application using a co-production process, and the key innovations are the resulting detail in societal factors and the understanding of complex interconnections between sectors. These findings are applicable not only in the limited local context in which we performed our work, but more broadly for those who conduct sustainability assessments which, by definition, include a social dimension.

Acknowledgements

This work is funded by The Ian Potter Foundation and Deakin University. The authors would like to thank Martin Butcher, Beth Sprunt, and Emma Ashton for their assistance with the systems mapping workshop. Emma Ligtermoet and Carina Wyborn provided valuable insights and expertise with respect to knowledge co-production which significantly aided in the development of this manuscript. Finally, the authors are grateful to two anonymous reviewers for their suggestions regarding how to improve the manuscript.

Data Availability Statement

The data generated from the systems mapping workshop is available at https://doi.org/10.5281/zenodo.7693729

References

Abram NJ, Henley BJ, Sen Gupta A, Lippmann TJR, Clarke H, Dowdy AJ, Sharples JJ, Nolan RH, Zhang T, Wooster MJ, et al. 2021. Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment* **2**(1): 8. doi: 10.1038/s43247-020-00065-8

Alcamo J, Thompson J, Alexander A, Antoniades A, Delabre I, Dolley J, Marshall F, Menton M, Middleton J, Scharlemann JPW. 2020. Analysing interactions among the sustainable development goals: findings and emerging issues from local and global studies. *Sustainability Science* **15**(6): 1561–1572. doi: 10.1007/s11625-020-00875-x

Allen C, Metternicht G, Weidmann T. 2017. An Iterative Framework for National Scenario Modelling for the Sustainable Development Goals (SDGs). *Sustain Dev* **25**(5): 372–385. doi: 10.1002/sd.1662

Anderson CC, Denich M, Warchold A, Kropp JP, Pradhan P. 2021 Oct 11. A systems model of SDG target influence on the 2030 Agenda for Sustainable Development. *Sustain Sci*, in press. doi: 10.1007/s11625-021-01040-8

Armstrong JH. 2022. Taking control to do more: how local governments and communities can enact ambitious climate mitigation policies. *Journal of Environmental Policy & Planning* **24**(2): 160–174. Routledge. doi: 10.1080/1523908X.2021.1992264

Bai XM, Surveyer A, Elmqvist T, Gatzweiler FW, Guneralp B, Parnell S, Prieur-Richard AH, Shrivastava P, Siri JG, Stafford-Smith M, et al. 2016. Defining and advancing a systems approach for sustainable cities. *Curr Opin Environ Sustain* **23**: 69–78. doi: 10.1016/j.cosust.2016.11.010

Bandari R, Moallemi EA, Lester RE, Downie D, Bryan BA. 2021 Oct 25. Prioritising Sustainable Development Goals, characterising interactions, and identifying solutions for local sustainability. *Environmental Science & Policy*, in press. doi: 10.1016/j.envsci.2021.09.016

Bandola-Gill J, Arthur M, Leng RI. 2022. What is co-production? Conceptualising and understanding co-production of knowledge and policy across different theoretical perspectives. *Evidence & Policy* **1**(aop): 1–24. Policy Press. doi: 10.1332/174426421X16420955772641

Basco-Carrera L, Warren A, van Beek E, Jonoski A, Giardino A. 2017. Collaborative modelling or participatory modelling? A framework for water resources management. *Environmental Modelling & Software* **91**: 95–110. doi: 10.1016/j.envsoft.2017.01.014

Beaudoin C, Mistry I, Young N. 2022. Collaborative knowledge mapping to inform environmental policy-making: The case of Canada's Rideau Canal National Historic Site. *Environmental Science & Policy* **128**: 299–309. doi: 10.1016/j.envsci.2021.12.001

Beck S, Forsyth T. 2020. Who gets to imagine transformative change? Participation and representation in biodiversity assessments. *Environmental Conservation* **47**(4): 220–223. Cambridge University Press. doi: 10.1017/S0376892920000272

Bennett NJ, Blythe J, Cisneros-Montemayor AM, Singh GG, Sumaila UR. 2019. Just Transformations to Sustainability. *Sustainability* **11**(14): 3881. Multidisciplinary Digital Publishing Institute. doi: 10.3390/su11143881

Bohunovsky L, Jäger J, Omann I. 2011. Participatory scenario development for integrated sustainability assessment. *Reg Environ Change* **11**(2): 271–284. doi: 10.1007/s10113-010-0143-3

Bond A, Morrison-Saunders A, Pope J. 2012. Sustainability assessment: the state of the art. *Impact Assessment and Project Appraisal* **30**(1): 53–62. Taylor & Francis. doi: 10.1080/14615517.2012.661974

Calvin K, Bond-Lamberty B. 2018. Integrated human-earth system modeling—state of the science and future directions. *Environmental Research Letters* **13**(6): 063006. IOP Publishing. doi: 10.1088/1748-9326/aac642

Chambers JM, Wyborn C, Klenk NL, Ryan M, Serban A, Bennett NJ, Brennan R, Charli-Joseph L, Fernández-Giménez ME, Galvin KA, et al. 2022. Co-productive agility and four collaborative pathways to sustainability transformations. *Global Environmental Change* **72**: 102422. doi: 10.1016/j.gloenvcha.2021.102422

Chambers JM, Wyborn C, Ryan ME, Reid RS, Riechers M, Serban A, Bennett NJ, Cvitanovic C, Fernández-Giménez ME, Galvin KA, et al. 2021 Aug 5. Six modes of co-production for sustainability. *Nat Sustain*: 1–14. doi: 10.1038/s41893-021-00755-x

City of Melbourne. 2022. United Nations Sustainable Development Goals: City of Melbourne voluntary local review 2022. Melbourne, Australia: City of Melbourne. Available at https://www.melbourne.vic.gov.au/SiteCollectionDocuments/un-sustainable-goals-voluntary-local-review.pdf. Accessed 2022 Apr 4.

Colac Otway Shire. 2021. Social Housing Plan - Colac Otway Shire: Shaping the Big Housing Build in Colac Otway Shire. Colac, Victoria: Colac Otway Shire. Available at https://www.colacotway.vic.gov.au/files/assets/public/trimfiles/council-and-the-shire/g21-regional-social-housing-project-2021-2022/colac-otway-shire-social-housing-plan-2021-adopted.pdf. Accessed 2023 Feb 14.

Cook D, Davíðsdóttir B. 2021. An appraisal of interlinkages between macro-economic indicators of economic well-being and the sustainable development goals. *Ecological Economics* **184**: 106996. doi: 10.1016/j.ecolecon.2021.106996

Cook D, Kaji TB, Davíðsdóttir B. 2023. An assessment of the scope and comprehensiveness of well-being economy indicator sets: The cases of Iceland, Scotland and New Zealand. *Ecological Economics* **205**: 107728. doi: 10.1016/j.ecolecon.2022.107728

Cooke SJ, Jeanson AL, Bishop I, Bryan BA, Chen C, Cvitanovic C, Fen Y, Forester J, Fürst C, Hu J, et al. 2021 Aug 17. On the theory-practice gap in the environmental realm: perspectives from and for diverse environmental professionals. *Socio-Ecological Practice Research*, in press. doi: 10.1007/s42532-021-00089-0

Costanza R, Daly L, Fioramonti L, Giovannini E, Kubiszewski I, Mortensen LF, Pickett KE, Ragnarsdottir KV, De Vogli R, Wilkinson R. 2016. Modelling and measuring sustainable wellbeing in connection with the UN Sustainable Development Goals. *Ecological Economics* **130**: 350–355. doi: https://doi.org/10.1016/j.ecolecon.2016.07.009

D'Alessandro S, Cieplinski A, Distefano T, Dittmer K. 2020. Feasible alternatives to green growth. *Nature Sustainability* **3**(4): 329–335. doi: 10.1038/s41893-020-0484-y

DELWP. 2014. *Effective Engagement: Building Relationships with Community and Other Stakeholders. The Engagement Toolkit*. The State of Victoria Department of Environment and Primary Industries. (Vol. 3).

Dupuits E, Cronkleton P. 2020. Indigenous tenure security and local participation in climate mitigation programs: Exploring the institutional gaps of REDD+ implementation in the Peruvian Amazon. *Environmental Policy and Governance* **30**(4): 209–220. doi: 10.1002/eet.1888

Easterling WE. 1997. Why regional studies are needed in the development of full-scale integrated assessment modelling of global change processes. *Global Environmental Change* **7**(4): 337–356. doi: 10.1016/S0959-3780(97)00016-2

Eker S, Rovenskaya E, Obersteiner M, Langan S. 2018. Practice and perspectives in the validation of resource management models. *Nat Commun* **9**(1): 5359. Nature Publishing Group. doi: 10.1038/s41467-018-07811-9

Fleming A, Bohensky E, Dutra LXC, Lin BB, Melbourne-Thomas J, Moore T, Stone-Jovicich S, Tozer C, Clarke JM, Donegan L, et al. 2023. Perceptions of co-design, co-development and co-delivery (Co-3D) as part of the co-production process – Insights for climate services. *Climate Services* **30**: 100364. doi: 10.1016/j.cliser.2023.100364

Fletcher M-S, Romano A, Connor S, Mariani M, Maezumi SY. 2021. Catastrophic Bushfires, Indigenous Fire Knowledge and Reframing Science in Southeast Australia. *Fire* **4**(3). doi: 10.3390/fire4030061

Folke C, Biggs R, Norström AV, Reyers B, Rockström J. 2016. Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society* **21**(3). doi: 10.5751/ES-08748-210341

Forsyth T. 2002. *Critical Political Ecology: The Politics of Environmental Science*. London: Routledge. doi: 10.4324/9780203017562

Gammage Bill. 2011. The biggest estate on earth : how Aborigines made Australia / Bill Gammage. Allen & Unwin Crows Nest, N.S.W.

Goetz AR, Vowles TM, Tierney S. 2009. Bridging the Qualitative–Quantitative Divide in Transport Geography. *The Professional Geographer* **61**(3): 323–335. Routledge. doi: 10.1080/00330120902931960

Gott B. 2005. Aboriginal fire management in south-eastern Australia: aims and frequency. *Journal of Biogeography* **32**(7): 1203–1208. doi: 10.1111/j.1365-2699.2004.01233.x

Hacking T, Guthrie P. 2008. A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment. *Environmental Impact Assessment Review* **28**(2): 73–89. doi: 10.1016/j.eiar.2007.03.002

Hajer M, Nilsson M, Raworth K, Bakker P, Berkhout F, de Boer Y, Rockström J, Ludwig K, Kok M. 2015. Beyond cockpit-ism: Four insights to enhance the transformative potential of the sustainable development goals. *Sustainability* **7**(2): 1651–1660.

van Hees S, Horstman K, Jansen M, Ruwaard D. 2020. How does an ageing policy translate into professional practices? An analysis of kitchen table conversations in the Netherlands. *European Journal of Social Work* **23**(2): 215–226. doi: 10.1080/13691457.2018.1499610

Holmes A. 2020. Researcher Positionality - A Consideration of Its Influence and Place in Qualitative Research - A New Researcher Guide. *Shanlax International Journal of Education* **8**: 1–10. doi: 10.34293/education.v8i4.3232

Horton R, Lo S. 2015. Planetary health: a new science for exceptional action. *The Lancet* **386**(10007): 1921–1922. Elsevier. doi: 10.1016/S0140-6736(15)61038-8

Jones P, Comfort D. 2020. A commentary on the localisation of the sustainable development goals. *Journal of Public Affairs* **20**(1): e1943. doi: 10.1002/pa.1943

Kain J-H, Söderberg H. 2008. Management of complex knowledge in planning for sustainable development: The use of multi-criteria decision aids. *Environmental Impact Assessment Review* **28**(1): 7–21. doi: 10.1016/j.eiar.2007.03.007

Kanter DR, Musumba M, Wood SLR, Palm C, Antle J, Balvanera P, Dale VH, Havlik P, Kline KL, Scholes RJ, et al. 2018. Evaluating agricultural trade-offs in the age of sustainable development. *Agricultural Systems* **163**: 73–88. doi: 10.1016/j.agsy.2016.09.010

Leach M, Rockstrom J, Raskin P, Scoones I, Stirling AC, Smith A, Thompson J, Millstone E, Ely A, Arond E, et al. 2012. Transforming Innovation for Sustainability. *Ecol Soc* **17**(2): 6. doi: 10.5751/es-04933-170211

Liu JG. 2017. Integration across a metacoupled world. *Ecol Soc* **22**(4): 19. doi: 10.5751/es-09830-220429

Martin M, Røyne F, Ekvall T, Moberg Å. 2018. Life Cycle Sustainability Evaluations of Bio-based Value Chains: Reviewing the Indicators from a Swedish Perspective. *Sustainability* **10**(2): 547. Multidisciplinary Digital Publishing Institute. doi: 10.3390/su10020547

Messori G, Brocchieri F, Morello E, Ozgen S, Caserini S. 2020. A climate mitigation action index at the local scale: Methodology and case study. *Journal of Environmental Management* **260**: 110024. doi: 10.1016/j.jenvman.2019.110024

Moallemi EA, Bertone E, Eker S, Gao L, Szetey K, Taylor N, Bryan BA. 2021. A review of systems modelling for local sustainability. *Environ Res Lett* **16**(11): 113004. IOP Publishing. doi: 10.1088/1748-9326/ac2f62

Moallemi EA, Gao L, Eker S, Bryan BA. 2022. Diversifying models for analysing global change scenarios and sustainability pathways. *Global Sustainability* **5**. Cambridge University Press. doi: 10.1017/sus.2022.7

Moallemi EA, de Haan FJ, Hadjikakou M, Khatami S, Malekpour S, Smajgl A, Stafford-Smith M, Voinov A, Bandari R, Lamichhane P, et al. 2021. Evaluating Participatory Modeling Methods for Co-creating Pathways to Sustainability. *Earth's Future* **9**(3): e2020EF001843. John Wiley & Sons, Ltd. doi: 10.1029/2020EF001843

Moallemi EA, Malekpour S, Hadjikakou M, Raven R, Szetey K, Moghadam MM, Bandari R, Lester R, Bryan BA. 2019. Local Agenda 2030 for sustainable development. *The Lancet Planetary Health* **3**(6): e240–e241. doi: 10.1016/S2542-5196(19)30087-7

Mochizuki J, Wada Y. 2022 Dec 22. Closing the loop of reflexivity. *Nat Clim Chang*: 1–3. Nature Publishing Group. doi: 10.1038/s41558-022-01569-1

Nam T. 2013. Citizen Participation in Visioning a Progressive City: A Case Study of Albany 2030. *International Review of Public Administration* **18**(3): 139–161. doi: 10.1080/12294659.2013.10805267

Ness B, Urbel-Piirsalu E, Anderberg S, Olsson L. 2007. Categorising tools for sustainability assessment. *Ecological Economics* **60**(3): 498–508. doi: 10.1016/j.ecolecon.2006.07.023

Norström AV, Cvitanovic C, Löf MF, West S, Wyborn C, Balvanera P, Bednarek AT, Bennett EM, Biggs R, de Bremond A, et al. 2020. Principles for knowledge co-production in sustainability research. *Nature Sustainability* **3**(3): 182–190. doi: 10.1038/s41893-019-0448-2

Ostrom E. 2010. Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change* **20**(4): 550–557. doi: 10.1016/j.gloenvcha.2010.07.004

Ostrom E. 2012. Nested externalities and polycentric institutions: must we wait for global solutions to climate change before taking actions at other scales? *Econ Theory* **49**(2): 353–369. doi: 10.1007/s00199-010-0558-6

Pascoe Bruce. 2014. Dark emu : black seeds : agriculture or accident? / Bruce Pascoe. Magabala Books Broome, Western Australia.

Purvis B, Mao Y, Robinson D. 2019. Three pillars of sustainability: in search of conceptual origins. *Sustainability Science* **14**(3): 681–695. doi: 10.1007/s11625-018-0627-5

Purvis B, Mao Y, Robinson D. 2021 Dec 14. A multi-scale integrated assessment model to support urban sustainability. *Sustain Sci*, in press. doi: 10.1007/s11625-021-01080-0

Randers J, Rockström J, Stoknes P-E, Goluke U, Collste D, Cornell SE, Donges J. 2019. Achieving the 17 Sustainable Development Goals within 9 planetary boundaries. *Global Sustainability* **2**: e24. doi: 10.1017/sus.2019.22

Reed MS, Graves A, Dandy N, Posthumus H, Hubacek K, Morris J, Prell C, Quinn CH, Stringer LC. 2009. Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management* **90**(5): 1933–1949. doi: 10.1016/j.jenvman.2009.01.001

Ruggerio CA. 2021. Sustainability and sustainable development: A review of principles and definitions. *Science of The Total Environment* **786**: 147481. doi: 10.1016/j.scitotenv.2021.147481

Sandberg M, Klockars K, Wilén K. 2019. Green growth or degrowth? Assessing the normative justifications for environmental sustainability and economic growth through critical social theory. *Journal of Cleaner Production* **206**: 133–141. doi: 10.1016/j.jclepro.2018.09.175

Secules S, McCall C, Mejia JA, Beebe C, Masters AS, L. Sánchez-Peña M, Svyantek M. 2021. Positionality practices and dimensions of impact on equity research: A collaborative inquiry and call to the community. *Journal of Engineering Education* **110**(1): 19–43. doi: 10.1002/jee.20377

Sedlacko M, Martinuzzi A, Røpke I, Videira N, Antunes P. 2014. Participatory systems mapping for sustainable consumption: Discussion of a method promoting systemic insights. *Ecological Economics* **106**: 33–43. doi: 10.1016/j.ecolecon.2014.07.002

Soergel B, Kriegler E, Weindl I, Rauner S, Dirnaichner A, Ruhe C, Hofmann M, Bauer N, Bertram C, Bodirsky BL, et al. 2021. A sustainable development pathway for climate action within the UN 2030 Agenda. *Nature Climate Change* **11**(8): 656–664. doi: 10.1038/s41558-021-01098-3

van Soest HL, van Vuuren DP, Hilaire J, Minx JC, Harmsen MJHM, Krey V, Popp A, Riahi K, Luderer G. 2019. Analysing interactions among Sustainable Development Goals with Integrated Assessment Models. *Global Transitions* **1**: 210–225. doi: 10.1016/j.glt.2019.10.004

Steffensen V. 2020. *Fire Country: How Indigenous Fire Management Could Help Save Australia*. Australia: Hardie Grant Explore.

Sterman JD. 2001. *Business Dynamics: Systems Thinking and Modelling for a Complex World*. Boston: Irwin/McGraw Hill.

Szetey K, Ashton E, Bradshaw S. 2020. The Forrest and District Plan: Towards 2030. Victoria, Australia. Available at https://www.forrestvictoria.com/wp-content/uploads/pdf/FDP2030-web.pdf.

Szetey K, Moallemi EA, Ashton E, Butcher M, Sprunt B, Bryan BA. 2021a. Co-creating local socioeconomic pathways for achieving the sustainable development goals. *Sustainability Science* **16**(4): 1251–1268. doi: 10.1007/s11625-021-00921-2

Szetey K, Moallemi EA, Ashton E, Butcher M, Sprunt B, Bryan BA. 2021b. Participatory planning for local sustainability guided by the Sustainable Development Goals. *Ecology and Society* **26**(3). doi: 10.5751/ES-12566-260316

Tan DT, Siri JG, Gong Y, Ong B, Lim SC, MacGillivray BH, Marsden T. 2019. Systems approaches for localising the SDGs: co-production of place-based case studies. *Globalization and Health* **15**(1): 85. doi: 10.1186/s12992-019-0527-1

The World Commission on Environment and Development. 1987. Our Common Future. Oxford/New York: Oxford University Press.

Trutnevyte E, Hirt LF, Bauer N, Cherp A, Hawkes A, Edelenbosch OY, Pedde S, van Vuuren DP. 2019. Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. *One Earth* **1**(4): 423–433. Elsevier. doi: 10.1016/j.oneear.2019.12.002

Turnhout E, Metze T, Wyborn C, Klenk N, Louder E. 2020. The politics of co-production: participation, power, and transformation. *Current Opinion in Environmental Sustainability* **42**: 15–21. doi: 10.1016/j.cosust.2019.11.009

UN. 2015. Transforming our world: the 2030 Agenda for Sustainable Development. New York, USA: UN General Assembly. Available at https://sustainabledevelopment.un.org/post2015/transformingourworld. Accessed 2019 Jul 22.

Verburg PH, Dearing JA, Dyke JG, Leeuw S van der, Seitzinger S, Steffen W, Syvitski J. 2016. Methods and approaches to modelling the Anthropocene. *Global Environmental Change* **39**: 328–340. doi: 10.1016/j.gloenvcha.2015.08.007

Voinov A, Farley J. 2007. Reconciling sustainability, systems theory and discounting. *Ecological Economics* **63**(1): 104–113. doi: 10.1016/j.ecolecon.2006.10.005

Voinov A, Jenni K, Gray S, Kolagani N, Glynn PD, Bommel P, Prell C, Zellner M, Paolisso M, Jordan R, et al. 2018. Tools and methods in participatory modeling: Selecting the right tool for the job. *Environmental Modelling & Software* **109**: 232–255. doi: 10.1016/j.envsoft.2018.08.028

van Vuuren DP, Batlle Bayer L, Chuwah C, Ganzeveld L, Hazeleger W, van den Hurk B, van Noije T, O'Neill B, Strengers BJ. 2012. A comprehensive view on climate change: coupling of earth system and integrated assessment models. *Environmental Research Letters* **7**(2): 024012. IOP Publishing. doi: 10.1088/1748-9326/7/2/024012

West S, Schill C. 2022. Negotiating the ethical-political dimensions of research methods: a key competency in mixed methods, inter- and transdisciplinary, and co-production research. *Humanit Soc Sci Commun* **9**(1): 1–13. Palgrave. doi: 10.1057/s41599-022-01297-z

Wyborn C, Datta A, Montana J, Ryan M, Leith P, Chaffin B, Miller C, van Kerkhoff L. 2019. Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice. *Annual Review of Environment and Resources* **44**(1): 319–346. doi: 10.1146/annurev-environ-101718-033103

Xu Z, Chau SN, Chen X, Zhang J, Li Yingjie, Dietz T, Wang J, Winkler JA, Fan F, Huang B, et al. 2020. Assessing progress towards sustainable development over space and time. *Nature* **577**(7788): 74–78. Nature Publishing Group. doi: 10.1038/s41586-019-1846-3

Yunkaporta T. 2019. *Sand Talk*. First. Melbourne, Australia: Text Publishing.

Zare F, Guillaume JHA, Jakeman AJ, Torabi O. 2020. Reflective communication to improve problem-solving pathways: Key issues illustrated for an integrated environmental modelling case study. *Environmental Modelling & Software* **126**: 104645. doi: 10.1016/j.envsoft.2020.104645

Zurba M, Petriello MA, Madge C, McCarney P, Bishop B, McBeth S, Denniston M, Bodwitch H, Bailey M. 2021 Jul 7. Learning from knowledge co-production research and practice in the twenty-first century: global lessons and what they mean for collaborative research in Nunatsiavut. *Sustain Sci*, in press. doi: 10.1007/s11625-021-00996-x