# Co-designing an integrated socio-ecological systems model for the Sustainable Development Goals

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# 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 difficult to predict. To understand how these interconnections play out at the local scale, we co-designed a systems model of the SDGs with a local community using a specific case study in Australia. In this paper, this multi-component model is fully documented, tested for uncertainty, and we have described a Business-As-Usual projection to illustrate its use. We found that integrating insights from local communities in a model co-design process can elicit far more societal interconnections between the SDGs compared to the current dominant model-building paradigm which typically does not involve meaningful stakeholder involvement. Social issues are often intensely local in origin and effect and attempts to model them at national or global scales may not succeed. Via local scale model co-design, we can tease out the interconnections between societal and non-societal issues and have a greater chance of identifying effective solutions to broader sustainability problems. Our results demonstrate that modellers alone are not fully aware of contextual differences and locally specific interactions that drive the behaviour of systems and SDG progress. Stakeholder participation at the local scale is critical for human-focused modelling that better appreciates local nuances. The local SDGs systems model fills a research gap between global, multisectoral, integrated models, and single-sector models applied to local case studies.

# Plain Language Summary

The Sustainable Development Goals (SDGs) are a United Nations agenda to guide nations around the world to achieve sustainability. To help nations reach the goals, we also need action from cities, businesses, and communities at the local level. The SDGs interact in complicated ways with each other and we need to use modeling to understand the best way to implement them without too many negative side-effects. We designed a complex model with a small regional community in Australia to understand where the benefits and side-effects might occur for their town. We discovered that by working collaboratively with the people in the community to design the model, we learned much more about the social interactions in their community to include in the model. This is a positive result because these social interactions are usually missed or left out of these types of models. We are able to include more nuanced and detailed information in the model and hopefully achieve a better overall outcome, meaning this is a good outcome for sustainability. This highly complex model, designed for the local level, is a new type of model and has not been researched before.

## Keywords

Sustainable Development Goals, local, system dynamics, multisectoral modelling, social, sustainability

# 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). The human-natural system is 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). It follows then, that modelling for sustainable development must also be integrated, multidimensional, and multi-scale if we wish to accurately represent human-natural (socio-ecological) systems. Global-, national- and sectoral-scale modelling for sustainable development has been well explored (Allen et al., 2019; Collste et al., 2017; Gao and Bryan, 2017; Moallemi et al., 2022; Philippidis et al., 2020; Randers et al., 2019; Soergel et al., 2021; van Soest et al., 2019), however there has been less focus on local scale modelling of the SDGs. The reasons for this are manifold, 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 lesser (Easterling, 1997). However, we argue that it is critically important to achieve sustainable development at the local scale to support national and global scale achievement (Bai et al., 2016; Hajer et al., 2015; Moallemi et al., 2019; Tan et al., 2019), and to do that we must also have mature modelling techniques at the local scale.

One modelling method that can characterise complex human-natural system interactions is systems modelling. In particular, system dynamics modelling (Sterman, 2001a) is ideal for analysing local sustainability interactions for multiple reasons (Moallemi, Bertone, et al., 2021): it has the capacity to model feedback interactions between multiple sectors (Papachristos, 2011; Pedercini et al., 2020); it is suitable for modelling the interconnections of the SDGs and their synergies and trade-offs (Randers et al., 2019); it can integrate both human and natural system processes (Tenza et al., 2017); and importantly for local-scale modelling, it is a fit-for-purpose method for participatory and co-design processes (Eker et al., 2018; Kimmich et al., 2019; Voinov and Bousquet, 2010). System dynamics is an approach which relies on understanding causal behaviours and eliciting feedback mechanisms within the model. In their review of scenario modelling tools for the SDGs, Allen et al. (2016) found that system dynamics models were best suited for the task of modelling at the national scale, and scored highest of all models tested for being “participatory, transparent and legitimate” (Allen et al., 2016: 205), indicating that system dynamics tools have advantages over others for inclusion and clarity. Multiple studies have examined system dynamics modelling for the SDGs (Allen et al., 2019; Barbier and Burgess, 2017; Collste et al., 2017; Zhang et al., 2016). Pedercini et al. (2020) discuss how sustainability is a complex problem requiring modelling technologies such as system dynamics that can deal with complexity. Likewise, Bai et al., (2016) considered a systems approach for modelling the SDGs in cities and argued that it was a robust technique for revealing hidden benefits and trade-offs and thus would translate to a more successful outcome for sustainable development. Despite the acknowledged importance of system dynamics for the SDGs, most of these models are global or national, and there are few examining multisector dynamics at the local scale.

Co-production of knowledge is an essential element of sustainability modelling (Chambers et al., 2021). Norström et al., (2020) proposed four principles for knowledge co-production: that it is context-based, pluralistic, goal-oriented, and interactive. These principles can be aligned with co-design modelling processes at the local scale for the SDGs. To ensure local context, localisation of the SDGs is key (Moallemi et al., 2019). A collaboration between researchers and stakeholders achieves pluralism, with the understanding that the community contains a diversity of knowledge and expertise with intersectoral lived experience (Cooke et al., 2021; Zurba et al., 2021). The goals around which the modelling is based are achieving the SDGs and fostering sustainability; and interactivity is encouraged with a range of active participation (Basco-Carrera et al., 2017; Voinov et al., 2018). These principles can be incorporated into local-scale modelling using system dynamics, as it was originally conceived as an “iterative process of joint inquiry between client and consultant” (Sterman, 2001b: 80). At a deeper level, Moallemi, de Haan, et al., (2021) developed a framework to encourage co-design practices in sustainability science, and Chambers et al., (2021) explored the variation in co-production for sustainability. These two papers explore the practical side of co-producing knowledge for sustainability and examine the potential benefits and challenges, as well as the contexts in which co-production and co-design might be applied. Moallemi, Bertone, et al., (2021) identified that co-production was infrequently employed in system dynamics modelling for sustainability even though the seminal text for the approach encouraged its practice (Sterman, 2001b).

In this paper, we co-design a new, multisectoral, local systems dynamics model for SDG analysis with a specific case-study community in southern Australia. The model was built using an understanding of the system gained from community engagement activities (reported in full in Szetey et al., 2021a, 2021b) and the sectors which defined the model boundary were identified from the concerns and sustainability ambitions of the local community, in a stakeholder-driven process for transparency and legitimacy (Nabavi et al., 2017). As part of an iterative process of model development, we used group model building techniques with open participation for the community to describe their understanding of the interconnections between sectors. This model building process was driven by the community, ensuring that we captured what mattered most to them. The purpose of this model is to inform decision-making for local sustainability by first mapping the system, and then later perturbing it to analyse its behaviour. Here we describe our modelling approach, the methods that we used to develop the model – co-designed with the community – and the results and testing of the completed model. 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 system dynamics modelling for the SDGs at the local scale: that ‘societal’ SDGs are insufficiently modelled; stakeholder participation was only reported in 28% of cases; and community-level modelling has not been widely used. We finish with a narrative describing the Business-As-Usual model and discuss what interventions are present in the model to explore sustainability pathways.

# 2. Methods

## 2.1. Modelling approach

Sustainability is a discipline which is defined by the interconnection of socio-ecological systems, and system dynamics is a modelling approach which has the capability to explore this (Moallemi, Bertone, et al., 2021). 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 a participatory modelling method to co-design our system dynamics model. We chose a set of participatory modelling approaches using the framework developed by Moallemi, de Haan, et al., (2021).

System dynamics modelling is a causal modelling paradigm which features interlinkages and feedbacks (Sterman, 2001a; Forrester, 2007; Papachristos, 2019). The mechanism is based upon differential equations, but is abstracted so that models can be constructed without an in-depth understanding of the mathematics using software tools such as Vensim (Ventana Systems, 2021). Within the models, there are variables known as *stocks* (which are mathematical state variables), *flows* (the derivatives or rate change equations), and *variables* (generally constants or other model parameters). We define combinations of these variables as *structures*, for example a stock variable with inflow and outflow variables would be described as a stock-and-flow *structure*. One benefit of this approach in the participatory modelling space is that the model variables are written as words (e.g., “population”, “migration rate”) rather than the traditional mathematical practice of using symbols, making it comprehensible to non-technical stakeholders.

System dynamics modelling is by nature an iterative process. That is, while the methods described below may seem like a linear series of steps, the reality of this type of modelling is that it involves continual revision and modification as modeller understanding of the system grows, stakeholder understanding of the modelling process grows, and as model complexity grows.

## 2.2. Modelling process

### 2.2.1. Understanding the case study

Our local case study is the town of Forrest, located in the Otways region of Victoria in south-eastern Australia. At the 2016 census there was a population of 231 people, and the town is a post-logging community with some agricultural activity, in transition to tourism and potentially other sectors. The Traditional Owners of the land are the Eastern Maar, a representative of whom participated in the group model building session described in section 2.2.2.3.

Forrest is located on the edge of the Great Otway National Park and contains two different bioregions within its domain – 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. Forrest has a history as 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.

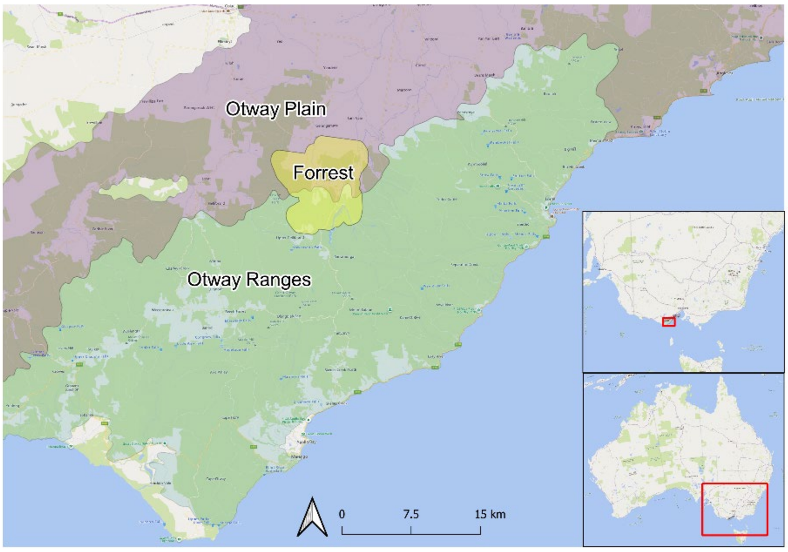


**Figure 1:** A map of the case study area. The two bioregions of Otway Plain and Otway Ranges are indicated in purple and green respectively. The township of Forrest is highlighted in yellow. There are two inset maps indicating the case study location in context of the state of Victoria and the country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

We undertook a range of engagement activities with the community which are more fully described in Szetey et al., (2021a; 2021b). These activities were intended to understand the local context and learn what was important (and not important) for local sustainability. Intentionally, the engagement work 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 engagement work became more targeted, further eliciting details about what in particular was important to the community with respect to each local SDG. For example, for SDG 8: *Decent work and economic growth,* we heard that the newly developed tourism sector was important, but the community did not want the local economy to be exclusively based around tourism. Additionally, there were flow-on issues related to housing availability as residential housing was being converted to tourism housing (also linked to SDG 11: *Sustainable cities and communities*).

As our understanding grew of the community's needs (opportunities, challenges, and threats), we developed a list of *driving forces* that the community believed would shape their future. These driving forces formed a major part of the Forrest and District Plan (Szetey et al., 2020), a co-produced document synthesising the knowledge gained from learning the community's sustainability ambitions (Szetey et al., 2021b). The engagement work underpinned our understanding of the Forrest system (Figure 2).

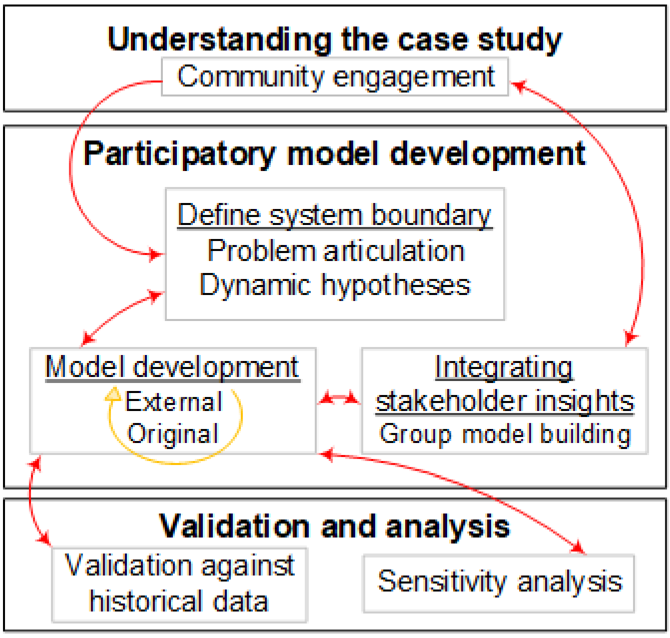


**Figure 2:** The process of model building. The unidirectional arrows indicate information flow (e.g., community engagement informed all steps in the participatory model development stage); and bidirectional arrows indicate iteration (e.g., validation and sensitivity analysis required further iterative model development). The circular arrow on model development indicates that this was iterative.

### 2.2.2. Participatory model development

#### 2.2.2.1. Defining the system boundary

The results of the community engagement activities provided us with a rich information set. These data, the local SDGs and the driving forces discussed in the previous section allowed us to define the system boundary, that is, the sectors within the community and township of Forrest which were of most concern to the local residents. In particular, the driving forces described each sector (e.g., population and demographics equated to the demographic sector; transport and connectivity to the transport and telecommunications sectors). Within our model we implemented feedback interactions in each sector in *model components,* which cover multiple socioeconomic and environmental SDGs such as economy, demographics, health and wellbeing, inequality, and biodiversity.

Having outlined this broad boundary, we developed our understanding of the components in greater detail using the method described by Sterman (2001b) for *problem articulation* and constructing *dynamic hypotheses.* This process entails defining the problems that the community expressed, and then constructing a hypothesis to explain how that problem arose and the contributing factors. For many of our problems, significant contributions from the Forrest community were made to the formulation of the hypotheses. For example, housing availability and affordability was noted as a problem by the community, and they suggested that tourism was one contributing factor, so in our dynamic hypothesis we included this local knowledge. However, tourism was not the only contributing factor, so this is where the researcher's emerging and iterative understanding of the system must also be incorporated (Figure 2).

#### 2.2.2.2. Developing the model

With the system boundary defined, we began the process of developing the model. Initially we conceptualised the system by sketching out each model component and the key variables, and visualising the way in which those components and variables interacted. Many tools can be used to achieve this, from pencil and paper through to software (e.g., PowerPoint, Visio, or Vensim). Fundamentally, we designed complexity into the model by piecing together model structures to represent each problem and its dynamic hypothesis. Some of these model structures were created 'from scratch', by identifying key variables and then analysing what inputs affected the behaviour of those variables; while other model structures were repurposed from existing, published systems models. Many systems models applied to case studies in the literature are sector-specific, e.g., water (Elsawah et al., 2009), energy (Cavicchi, 2018), agriculture (Bastan et al., 2018), and for local scale modelling these are a rich resource for building an integrated model of a complex socio-ecological system.

We reviewed existing system dynamics models to identify those which may be applicable to our case study. This was an iterative process, with many external model structures included and then later discarded, or highly modified. The FeliX model (Rydzak et al., 2010) was found to be of great relevance and it inspired not only with its model structures (for SDGs 3, 8, 11, 13, and 15), but also its documentation and development process (Rydzak et al., 2013). Other examples of integrated model structures included the demographic model (SDG 11, Navarro and Tapiador, 2019) and the road quality structure (SDGs 3 and 11, Fallah-Fini et al., 2015). Conversely, we considered the wildfire model from Collins et al., (2013) for SDGs 13 and 15, but concluded that it was too complex for our requirements.

However, many structures within the model required designing from the ground-up, such as the public transport (bus demand) structure, and the telecommunications component. The economy component was split into three replicated economic sub-sectors (agriculture, tourism, and other), and we used a Cobb-Douglas function to model productivity for each of those economic sub-sectors (Angulo et al., 2015). Each decision we made in developing the model was guided by the understanding we had of the Forrest system from our work with the community (Figure 2).

We built the model using Vensim DSS (Ventana Systems, 2021) and the full model file and documentation of each variable is available in the Supplementary Information. The model documentation includes data sources, system conceptualisation for each model component, and the formula, units, and assumptions for every model variable. The data and code used is available in the Supplementary Information (section S6). We aimed to be as transparent and reproducible as possible with our model documentation and have followed reporting guidelines developed by Rahmandad and Sterman (2012).

#### 2.2.2.3. Integrating stakeholder insights

We conducted further work with the community in a group model building workshop (Vennix, 1996) in which they could design and define the interconnections between the model components independently of our work. This process was designed to refine and extend the model by providing a second dataset which we could then use to test and build upon the work we had already done. This strategy also had the benefit of not biasing the workshop participants toward the model we had designed, which we felt could be a risk. We conducted the group model building workshop after completion of the first 'draft' of the model.

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 (Figure 3). The workshop design details are available in the Supplementary Information (S3). This information was then used to iteratively improve the model we had designed, for example, by modifying the existing design, or alternatively incorporating entirely new structures such as travel equity and cultural burning.

**Figure 3:** Three images from the group model building workshop (image credit: Enayat A. Moallemi).

### 2.2.3. Model validation, sensitivity analysis and BAU projection

To assess which variables were more influential on the behaviour of the model, we selected an initial pool of 93 input (Table S2) and 47 output (Table S3) variables across different model components. Due to the computational demand required to test many variables, we refined the number to 28 (Table S4) and 9 (Table S5) of the most influential variables, respectively, selected through initial sensitivity analysis. The initial uncertainty bounds tested were a symmetrical ±30% variation around the reference value, which were refined if required (for example, a 30% variation in disability fraction or internet access was impractical; and variation for exponents were also reduced as these are highly sensitive in context). Testing was performed using the Exploratory Modelling Workbench Python package (Kwakkel, 2019). The code and model file used for all the following analyses are available in the Supplementary Information (section S6). Both the validation and sensitivity analysis exposed flaws in the model, which required us to make modifications and then re-test, which is another essential part of the iterative model building process (Figure 2).

To validate the model and ensure it accurately represented past behaviour in the system, we compared historical data for a range of variables against our base model run and a set of 20,000 exploratory sampling runs using Latin Hypercube sampling. The sampling used the 28 influential input variables (Table S4), and the output variables to compare against historical data were taken from four of the twelve model components (*Demographic, Economy, Land Use* and *Climate change*). These were chosen as they featured the best sources of historical data available to validate the model. These data were principally obtained from Australian Bureau of Statistics census data (Australian Bureau of Statistics, 2017), but a limitation existed for certain data as Forrest was not recorded as an independent statistical area prior to the 2006 census. This meant there were only three data points (from 2006, 2011 and 2016 censuses) for seven of the twenty validation variables. The results of the Latin Hypercube sampling for these twenty variables were plotted as an envelope between the minimum and maximum values. The data used for the variables in the *Climate change* component (DELWP, 2021; Bureau of Meteorology, 2021; CSIRO, 2021) were much more comprehensive and we used these data to create linear models, which formed the model variables "Forest Fire Danger Index", "Annual Rainfall", "Average Max Temperature", and "$CO_2$". We plotted these linear models against historical data to demonstrate the fit of the data.

We measured the uncertainty of the influential variables (Tables S4 and S5) using Morris elementary effects sampling with 2000 simulations, and represented the sensitivity using the normalised values of the Morris index $\mu*$. $\mu*$ indicates the overall effect of inputs on an output variable and ranks the inputs by strength of effect. This method was chosen as it is suitable for complex, non-linear feedback models. The results generated from Morris elementary effects sampling are efficient in computational time and reliable (Campolongo et al., 2007; Gao and Bryan, 2016). We visualised the Morris sampling results by plotting as a density cloud to understand if the sampling produced a diffuse output (indicating greater uncertainty), or a more concentrated output (indicating lesser uncertainty), centred around a median line.

We set our simulation range for the model to run from the year 2000 (to validate historical data) to 2050 (to give a medium-long term projection of the results of SDG implementation). The illustrative results discussed in this paper describe settings for Business as Usual (BAU) conditions, i.e., following recent and expected trends in key drivers. The BAU settings are fully described in the model documentation provided in the Supplementary Information. Structures were included in the model for other intervention scenario simulations, but which are not implemented in the BAU analysis.

# 3. Results

## 3.1. Participatory local SDGs systems model

### 3.1.1. System boundary

The engagement work with the community resulted in 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 driving forces that were identified 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 model components which delineated the system boundary for the model: *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 driving forces; except that 'local school' was incorporated into the *Demographic* component, 'transport and connectivity' were split into separate components ('connectivity' referring to telecommunications), and *Health and wellbeing* was established as a separate component because of SDG 3. SDG 6 and 11 were represented across multiple components: SDG 6 in *Housing, Health and wellbeing* and *Infrastructure;* SDG 11 in *Demographic, Land Use, Economy, Housing, Transport, Tourism, Climate change, Infrastructure,* and *Inequality.* Figure 4 shows the model components, broadly describes what each component comprises, and identifies the local SDGs relevant to each.

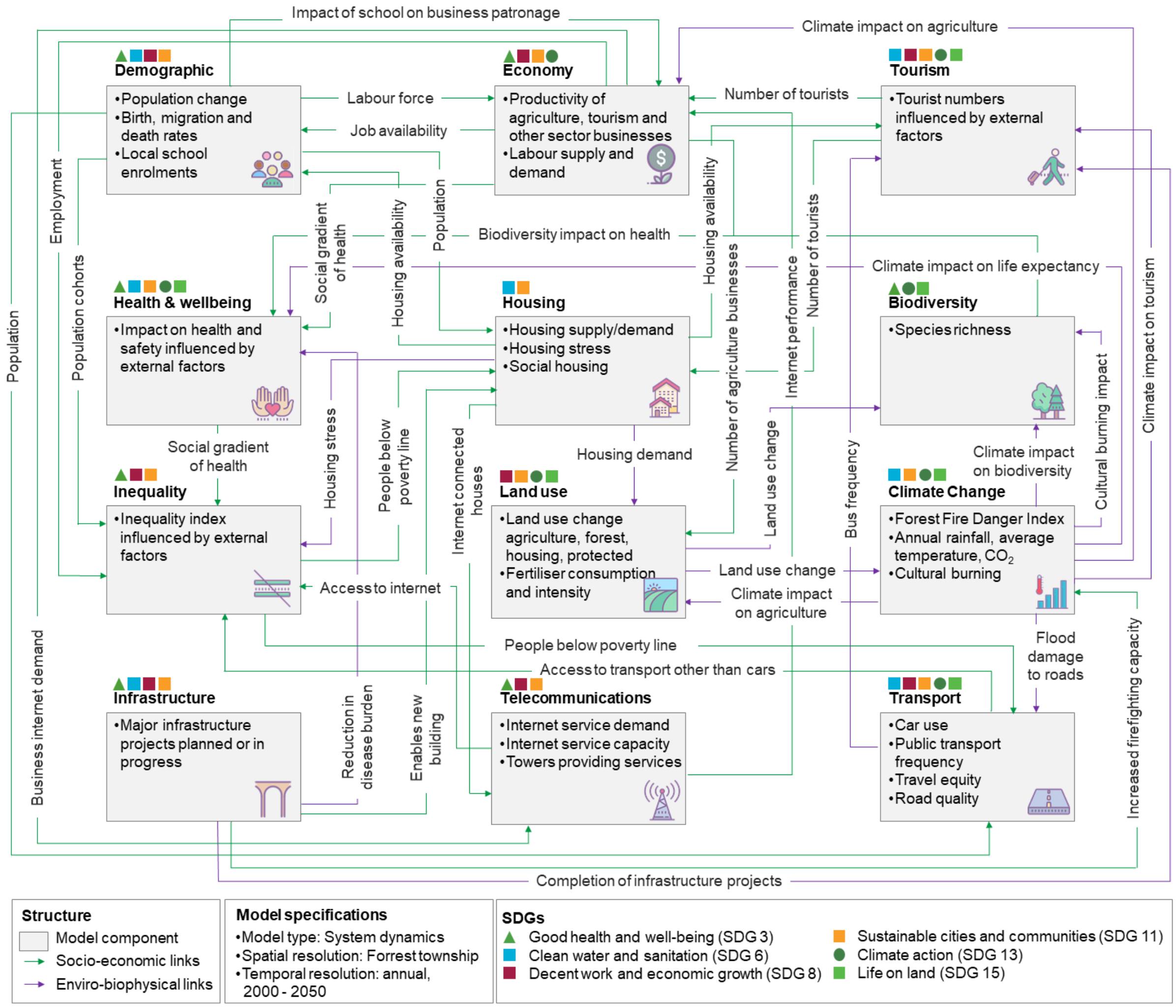


**Figure 4:** The interactions between the twelve model components (adapted from Figure S2 in Moallemi et al., (2022)).

With the wide range of model components, there is an analogous range of sectoral problems and dynamic hypotheses 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. The full list of problem articulations and dynamic hypotheses that describe each model component are listed in the Supplementary Information (Table S1), however here we provide one from the *Housing* sector as an example:

> *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.

### 3.1.2. Model description

The local SDG systems model contains 392 variables. There are many interconnections between the model components, represented in Figure 4 by linking arrows. For example, there are six ‘outgoing’ connections for the model component *Climate change*, and five for the components *Housing, Economy,* and *Population,* indicating that these components have the broadest impact on other model components. 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. Inversely, *Inequality* has five ‘incoming’ connections, and *Health and Wellbeing, Tourism, Economy,* and *Housing* have four, signifying that these are the model components which are most impacted by the others. Characterising these interconnections helps to gain understanding of any counterintuitive behaviour (especially cross-sectoral) that may have occurred in the model, and also to identify levers for interventions.

At a deeper level, we can isolate some of the cross-sectoral interconnections and identify where feedback loops occur. In Figure 5, we have selected five feedback loops that we believe play an important role in the Forrest system (these are not the only feedback loops present in the system, important or otherwise). The telecommunications-economy loop (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. Examples (b), (c), and (d) in Figure 5 are similar; however example (e) does not present a feedback loop but instead shows how climate change is a *pressure*. This is reflected in the *Climate change* component (Figure 4) where most of the connections are outward. This is even more pronounced with the *Infrastructure* component, which exclusively has outward connections. This does not mean that there are no inward influences on these components the system, but rather that these are less significant and are not modelled within the local SDGs systems model. We discuss this further in section 4.3.

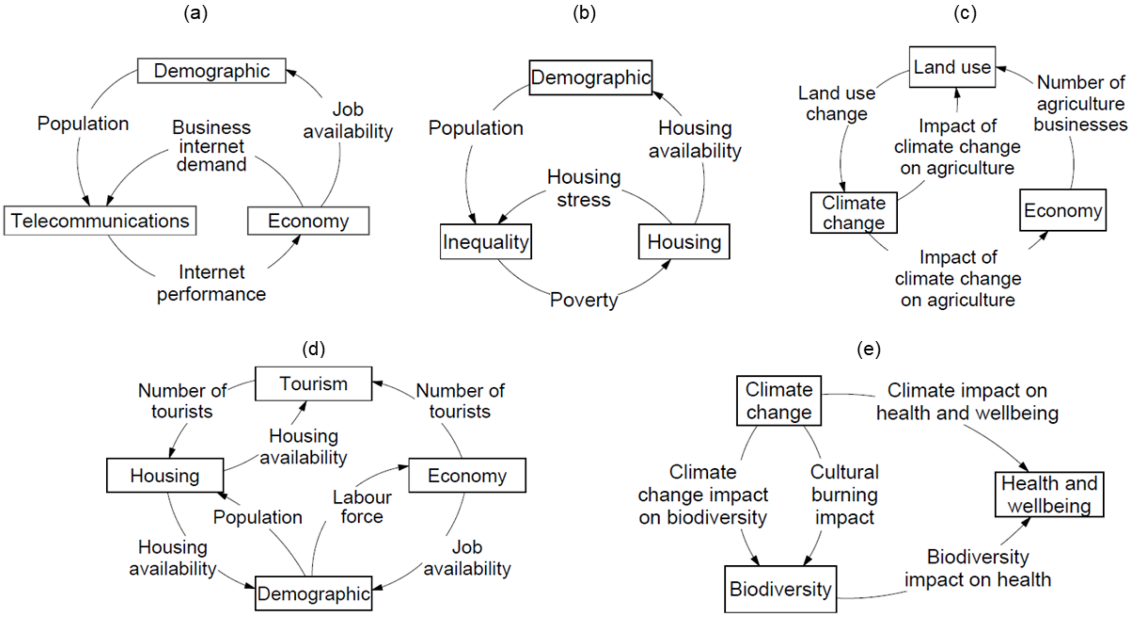
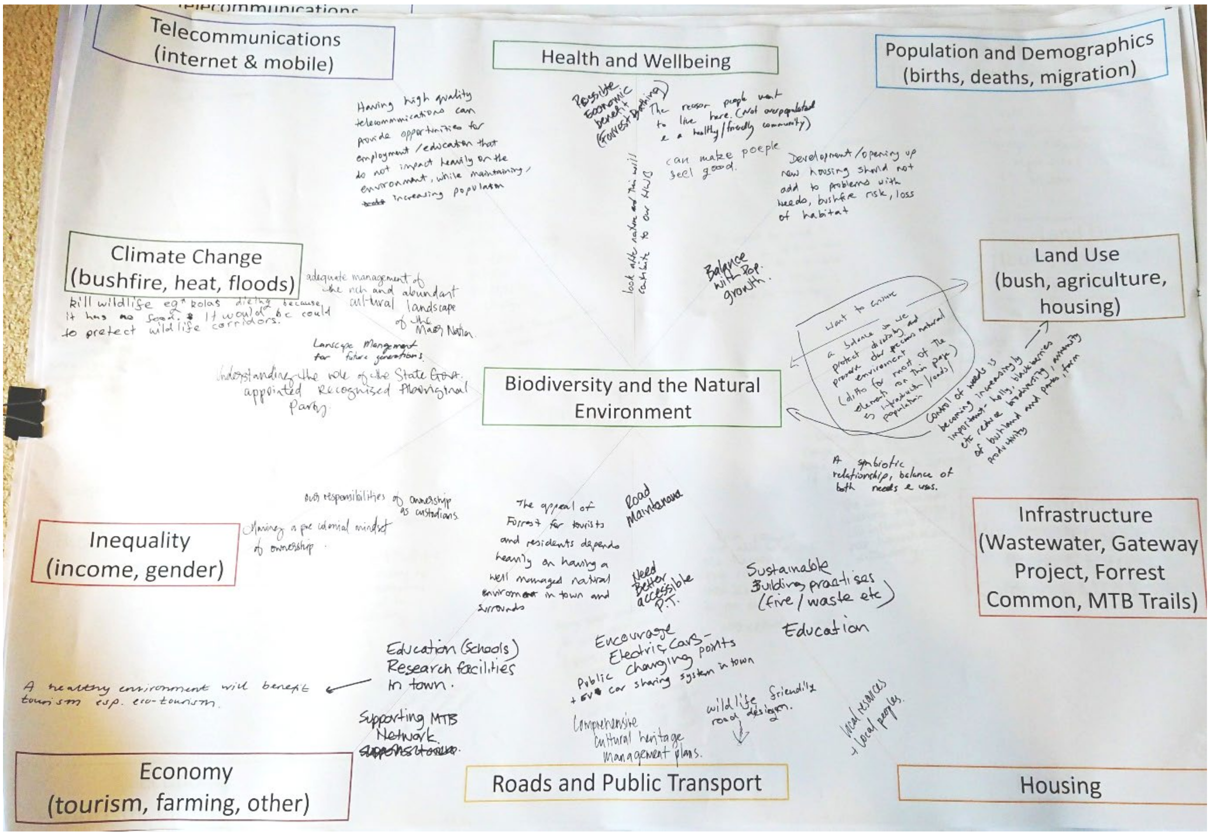


**Figure 5:** Five cross-sectoral feedback loops. (a) telecommunications-economy loop; (b) inequality-housing loop; (c) land use-climate change-economy loop; (d) tourism-economy-housing loop; (e) climate change-biodiversity-health and wellbeing loop.

The externally sourced model structures which form part of or inspired our final model are referenced in section S2 of the Supplementary Information. We have provided figures of each model component (section S5) and the complete model documentation is available in the Supplementary Information.

### 3.1.3. Stakeholder-driven model refinement

We had 22 participants at the workshop. This activity produced a rich dataset of responses which went beyond simply defining the interconnections between sectors. We have provided the complete set of poster responses in the Supplementary Information (section S4), but here we show one example (Figure 6) to demonstrate the results obtained, and have summarised the responses for another example (Table 1). Examples of modifications made to the local SDGs systems model in response to these insights included incorporating a cultural burning structure in the *Climate change* component, satisfying the community's desire for Indigenous land management and greater cultural connection; including a structure for social housing, which does not currently exist in Forrest but can be 'switched on' in the model for simulation of sustainability pathways; and designing a structure to understand the role that improved public transport could play in Forrest.



Having high quality telecommunications can provide opportunities for employment / education that do not impact heavily on the environment, while maintaining / increasing population

Possible Economic benefit (Forrest Bathing)

The reason people want to live here. (Not overpopulated & a healthy / friendly community)

can make poeple feel good.

look after nature and this will contribute to our HWB

Development / opening up new housing should not add to problems with weeds, bushfire risk, loss of habitat

Balance with Pop. growth.

adequate management of the rich and abundant cultural landscape of the Maar Nation.

kill wildlife eg. kolas dieing because it has no food. It would be could to protect wildlife corridors.

Lanscape Mangement for future generations.

Understanding the role of the State Govt. appointed Recognised Aboriginal Party.

Want to ensure a balance so we protect diversity and preserve our precious natural environment (ditto for most of the elements on this page) vs infrastructure / roads / population

Control of weeds is becoming increasingly important - holly, blackberries etc reduce biodiversity, amenity of bushland and parks, farm productivity

A symbiotic relationship, balance of both needs & uses.

our responsibilities of ownership as custodians.

Having a pre colonial mindset of ownership.

The appeal of Forrest for tourists and residents depends heavily on having a well managed natural environment in town and surrounds

Road Maintenance

Need Better accessible P.T.

Sustainable Building practises (fire / waste etc)

Education

Education (Schools) Research facilities in town.

A healthy environment will benefit tourism esp. eco-tourism.

Encourage Electric Cars - charging points

Public + EV car sharing system in town

Supporting MTB Network

Comprehensive cultural heritage management plans.

wildlife friendly road design.

local resources + local peoples.

**Figure 6:** One example of a completed poster from the group model building workshop. The poster is for how the biodiversity sector (centre) interacts with the other sectors.

**Table 1:** 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 (internet & mobile) | People experiencing income inequality can't afford the internet or a phone.<br>How do we share key information in real-time when access to communications is unequal? |
| Climate change (bushfire, heat, floods) | Inequality means those who are at a greater disadvantage will be more affected by climate change and its negative impacts. |
| Biodiversity & the natural environment | How can the local community incorporate Traditional Owner knowledge when Traditional Owners can't afford to live in Forrest?<br>The dispossession of First Nations peoples and the change to landscape occurred for personal gain rather than Country wellbeing. |
| Economy (tourism, farming, other) | Forrest should provide programs for those on low incomes to support entry to markets, develop business ideas – mentoring, finance, education. |
| Health & wellbeing | Embedded inequality, stigma, and discrimination results in poor health outcomes.<br>People experiencing inequality are more stressed and have poorer health than those who do not.<br>There is intergenerational inequality in Forrest and understanding this is important for developing solutions for health and wellbeing. |
| Roads & public transport | Many groups need access to good public transport (young, old, low-income, disabled, without licence, etc).<br>Car sharing scheme could provide low-cost transport, especially if the cars are electric vehicles. |
| Population & demographics (births, deaths, migration) | It would be good to maintain a diverse mix of people in Forrest, rather than having it become a playground for wealthy people.<br>Vacant possession brings about inequality. |
| Land use (bush, agriculture, housing) | Need a social housing option to control the market forces which are leading to tourism housing conversion and driving up housing prices. |
| Infrastructure (wastewater, Gateway Project, Forrest Common, mountain-bike trails) | The way wastewater solutions are costed will affect rich and poor households differently.<br>Hopefully new infrastructure will provide a greater range of jobs for more locals, leading to better wealth distribution in the community. |
| Housing | High house prices are pushing out community members who cannot afford to live in Forrest anymore, lowering community cohesion. |

## 3.2. Model validation, sensitivity analysis, and BAU projection

### 3.2.1. Model validation

The results of the exploratory Latin Hypercube sampling are shown in Figure 7, plotted against historical data. Given the limitations of data for some variables (explained in section 2.2.3), the visual inspection of the validation plots and sampling envelopes in Figure 7 indicates a satisfactory fit of the historical data for all validation variables. Some deviations from the data and sampling are visible, e.g., Forest Land and Housing Land, but the nature of feedbacks in the model make some of these deviations unavoidable. For instance, the Land Use model structure is comprised of a loop where land is transferred between each land use type. If the model results demonstrate a match with the general trend of the historical data (as it does with Forest and Housing Land), while accuracy is preserved elsewhere, this is usually sufficient.

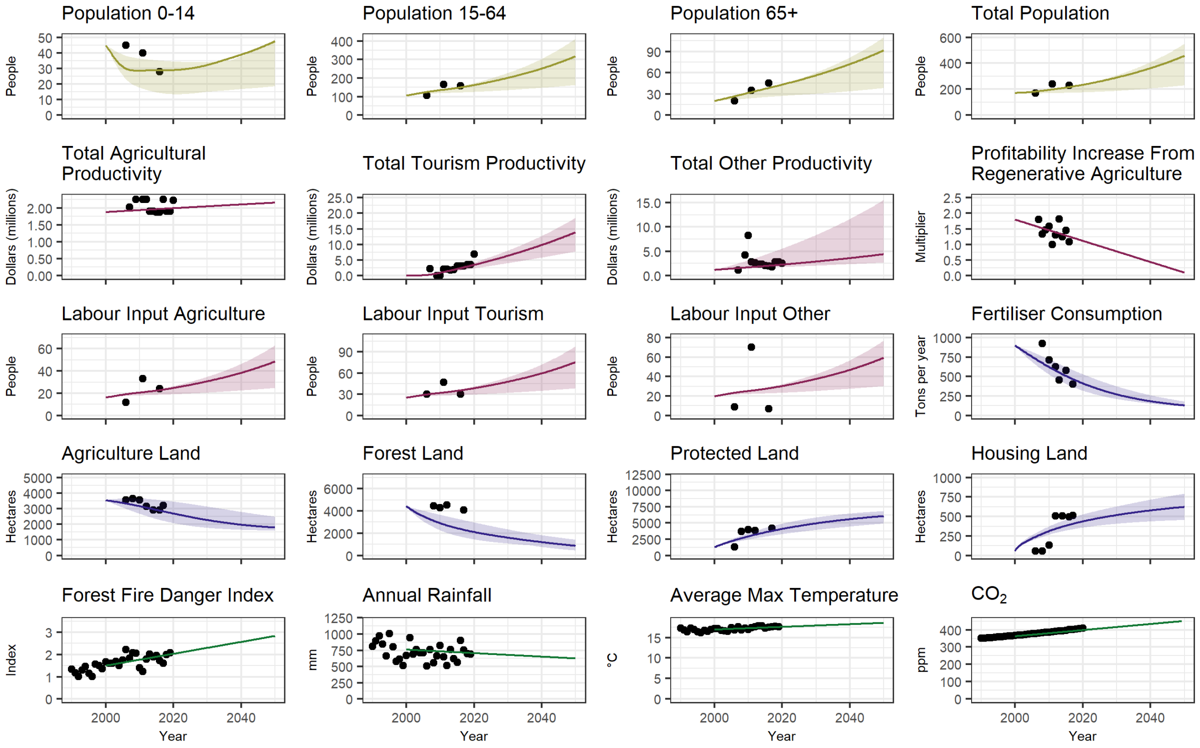


**Figure 7:** Plots for 20 variables for validation of the model against historical data. The base model run data is represented by the coloured line on the plot; the shaded area enclosing the line is the envelope between maximum and minimum values for 20,000 exploratory sampling runs; and the black dots represent the historical data. The plots for Total agricultural productivity and Profitability increase from regenerative agriculture do not appear to have envelopes, but the sampling runs were all a close fit to the model run line. Note the bottom row of plots do not show a sampling envelope but are included here to show the fit of the model run to the historical data. The colour on the plots indicates the model component to which each variable belongs.

### 3.2.2. Sensitivity analysis

The sensitivity of model variables was tested using Morris elementary effects sampling. The 9 tested output variables (Table S5) range across the different model components and ranking of influence of the input variables on the outputs is shown in Figure 8. The most influential variables are migration rate for the youth cohort (age 0-15; affecting six output variables), the migration rate for the adult cohort (affecting four), and the mortality rate for the retired cohort (age 65+) and fertility rate (both affecting three). The influential variables appear to cluster together in particular model components (e.g., *Demographic, Inequality* and *Housing; Telecommunications* and *Economy*), which reflects the feedback loops in Figure 5 and could potentially identify new feedback loops that were not included in that figure.

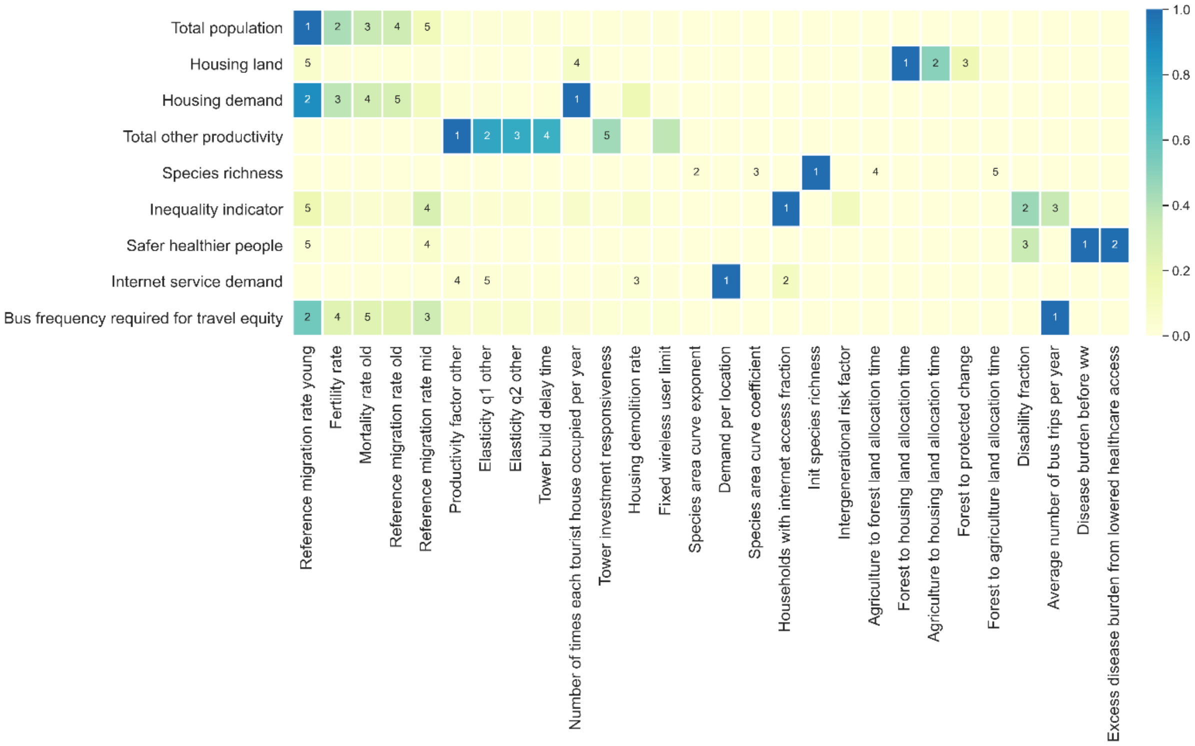


**Figure 8:** The sensitivity of model parameters across 9 outcome variables. The nine output variables are on the y axis and the 28 input variables are on the x axis. The five most influential input variables for each output variable are numbered on the heatmap, and the level of influence for each input variable is shown through colour intensity.

In Figure 9, we plotted the results of the sensitivity analysis for the nine selected output variables. These results are shown as a density cloud for the 2000 model simulations. Some variables had much broader uncertainty ranges (e.g., Species Richness, Bus Trips for Travel Equity) than others which track more closely to the median line (e.g., Safer Healthier People, Internet Service Demand), demonstrating the effects of the uncertainties of the input variables (many of which are subject to assumptions; see model documentation in the Supplementary Information for assumptions recorded for each model variable). Inspecting Figure 8 and Figure 9 together shows that the species richness variable has high uncertainty, and the key input variable which contributes to this is *INIT species richness*, which is the initial value for species richness at the commencement of the simulation. This is a highly uncertain parameter because while we can estimate the number of species in an area, it is infeasible to know this value to a high degree of certainty. The implication of this for the local SDG systems model is that these very uncertain parameters will then propagate their uncertainty to other sectors within the system; so in the case of species richness, looking at loop (e) in Figure 5, we can expect that this uncertainty will also affect the results in the *Health and wellbeing* model component.

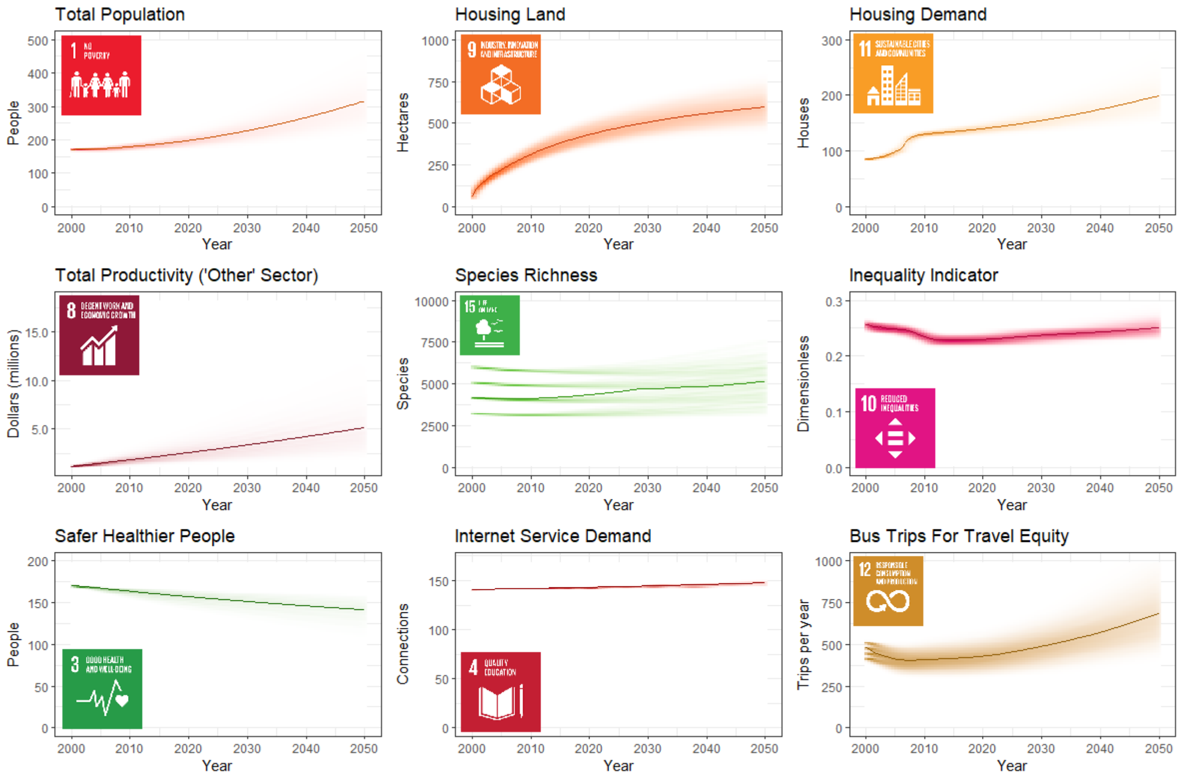


**Figure 9:** The uncertainty ranges from the sensitivity analysis of 9 outcome variables. These are represented as a density cloud with the median of all simulations shown as a line. Note some parameters have a higher initial uncertainty (e.g., species richness, bus trips for travel equity).

### 3.2.3. The BAU results interpretation

The model results described in this manuscript were run on a Business As Usual (BAU) scenario. That is, we identified the current drivers and trends and assumed no change. The plots shown in Figure 7 and Figure 9 also provide an example of the projections to 2050 produced by the model under this scenario. The demographic projections show a slowly increasing population over 50 years (SDG 11), principally driven by the 15-64 age cohort, and the uncertainty plot indicates increasing uncertainty over time (as the density cloud becomes diffuse). This leads to increasing housing demand and therefore greater need for housing land (SDG 11). Economic productivity is projected to have the greatest growth in the tourism sub-sector, and moderate uncertainty in the 'other' sub-sector (SDG 8). The number of *Safer Healthier People* is likely to decrease (SDG 3 and 6; driven by disease from failing wastewater infrastructure, and lowered access to healthcare), and factors contributing to inequality remain relatively steady (SDGs 1, 2, 3, 5 and 10), indicating that some work is required to improve outcomes for health and inequality in the community. Species richness and protected land are projected to increase – although with a significant amount of uncertainty for species richness – indicating promising outcomes for biodiversity (SDG 13 and 15). The projection regarding species richness is counterintuitive with respect to the biodiversity crisis unfolding around the world (IPBES, 2019), however the main driver for this is an increase in protected land (i.e., national park), which supports biodiversity. Therefore, *at the local scale*, an increase in biodiversity is seen which does not match national or global patterns.

Here we summarise the key findings of the model simulation as a narrative:

> In the period between 2000 and 2050, Forrest sees a slowly increasing population to approximately 450 people, driven mostly by adults (age 15-64) and retirees (65+). Enrolments at the local school are constant until 2030, after which they slowly increase. Housing land and

> protected land (national park) both increase – only a small increase for housing land but a large one for protected land – and agriculture and forest land both decrease. The land appears to be transferring from forest and agriculture to protected. Fertiliser consumption is decreasing, broadly in line with historical trends as well as the decrease in agricultural land. Residential and tourist housing supply both reach a maximum value and do not change, as expected with the limits imposed by existing septic tank wastewater treatment. Rent and mortgage stress remain relatively constant, with costs increasing and no additional housing supply to ease demand. Despite a decrease in agricultural land, agricultural economic productivity maintains a small increase. Tourism sees a steady, relatively fast increase in line with historical trends, and the "other" economic sector also sees small but significant productivity growth. The number of tourists visiting Forrest reaches a ceiling value but remains constant from about the mid-2010s (the impact of the pandemic and lockdowns is not explicitly modelled), held in check by the lack of housing growth. Species richness experiences a decline through the first 20 years, but then rebounds, likely due to the increase in protected land. Inequality remains relatively steady over time but there is a general increase in inequality in the last 20 years. This may be in line with the decrease of Safer Healthier People over the 50-year time frame, as the low-income population increases, as does climate risk. There has been no new wastewater infrastructure so the disease burden has not decreased. Internet service demand increases with the population but no new fixed wireless towers have been built to increase capacity. The only completed infrastructure project is the Mountain Bike Trail improvements which commenced in 2021. Bus services have not increased and travel equity remains a problem.

This narrative identifies many of the interventions that can be implemented to induce changes. This is discussed further in section 4.5.

# 4. Discussion

We have used participatory methods to design a local-scale system dynamics model for informing interventions for the Sustainable Development Goals. There were two aspects to these participatory methods: the initial localisation process of the SDGs and development of local sustainability pathways (Szetey et al., 2021a) which were used to inform the design of the first draft of the model; and the refining and extending of the model using group model building techniques. We focused on the gaps identified by Moallemi, Bertone, et al., (2021), namely the modelling of societal factors, stakeholder participation, and greater attention to the interconnections between sectors. The final design of the model incorporates many structures that we learned about exclusively through the co-design process, and the scope and detail of the local SDGs systems model may exceed that of any other model previously made for a community of this size. We consider this to be a direct result of the collaboration between researchers and the community of Forrest and the co-design process we employed, which provided a rich source of data to draw upon to first build, and then refine and extend the model.

## 4.1. Model co-design

The benefits of stakeholder participation in modelling studies has been well explored (Basco-Carrera et al., 2017; Vennix, 1996; Voinov et al., 2016; Voinov and Bousquet, 2010), and is even more crucial at the local scale (Moallemi, de Haan, et al., 2021) and yet Moallemi, Bertone, et al., (2021) found that only 28% of local-scale system dynamics modelling for the SDGs involved stakeholders. This is despite the original conceptualisation of system dynamics as a dialogue between modellers and stakeholders (Sterman, 2001b).

In developing the local SDGs systems model, engagement with stakeholders in Forrest significantly deepened our understanding of the system. The contextual analysis we conducted (Szetey et al., 2021a) did not give the insights that engaging with the community face-to-face did. For example, we learned about the tensions between housing and tourism; the structural inequality present in the community; their love for the local environment and desire for Indigenous connection to Country; and problems with internet connectivity. These are factors which ended up being critical parts of the model but which could not be learned from a desktop review of documents. Through the group model building workshop, local understanding of the Forrest system further improved the model by refining and extending upon our initial work. We have previously referred to the cultural burning and travel equity structures which resulted from the co-design workshop, but other extensions included modelling the impact on healthcare access from living rurally; social housing; and a significant change to the *Housing* component which included housing costs, accounting for rented and mortgaged properties and incorporating housing stress.

As a modelling community, the merits of stakeholder participation have been known for some years (e.g., Kok et al., 2021; Voinov et al., 2014). Planners and local authorities have been utilising participatory methods for decades (Andrews and Turner, 2006; Bodorkós and Pataki, 2009; Brody et al., 2003; Burby, 2003; Reed, 2008). Sterling et al., (2019) reflect upon their participatory modelling experience and the lessons learned, which is an excellent resource for all modellers, veteran or novice, to promote engagement with stakeholders in the process of co-designing systems models for sustainability. Our results demonstrate the benefits of co-design and stakeholder participation for a more inclusive and accurate modelling outcome.

## 4.2. Modelling social elements

The local SDGs identified in Szetey et al., (2021a) included the societal SDGs *Good health and wellbeing* (SDG 3) and *Sustainable cities and communities* (SDG 11). Here we adopt the SDG dimensional classification defined by Folke et al., (2016). However, because of the interconnected nature of our multisectoral system, omission of societal *factors* beyond these two societal SDGs within the model would have rendered it incomplete (e.g., SDG 10 Reduced Inequalities is not a local SDG but *Inequality* is a model component). We included model components representing societal elements of demography (i.e., human population dynamics), housing, health and wellbeing, inequality, telecommunications (a socio-technical component representing how humans interact with telecommunications), and transport (a component which includes a structure modelling travel equity). We modelled these societal elements endogenously within the model, as these are key factors to 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-design process revealed a much richer narrative around the social components of sustainability.

The environmental and economic components of sustainability are, in general, easier to measure quantitatively and thus perhaps more generalisable across case studies. However, we found considerable nuance in the social aspects that we could only learn via a co-design process. It 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* component, it was not conceived as a social equity problem. 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 co-design, with comments such as "Many groups need access to good public transport (young, old, low-income, disabled, without licence, etc)", "Accessible transport to Colac 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 1; Section S3). Indeed, the co-design process drew out far more social interactions between model sectors than any other type of interaction, a finding that is supported by Beaudoin et al., (2022).

## 4.3. Model interconnections

Understanding the interconnections between model components gives us a gauge for knowing where to place interventions for the greatest effect. It is clear from Figure 4 that *Climate change* is one of the model components with the greatest outward interconnection. While climate change mitigation is an area in which little can be done at the local scale, more can be achieved on climate adaptation and this is evident within the model. For example, the model structure for 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, implying that inequality is a multifaceted and complex problem. As this component's structure is that of an indicator, it necessarily has many inputs from other components. Some of the factors in this inequality indicator were accepted contributors to inequality, such as unemployment (from *Economy*), poverty, and disability, but the co-design process highlighted additional factors such as travel inequality (from *Transport*), housing stress (from *Housing*), and intergenerational inequality (from *Demographics*).

We heard from our stakeholders that one of the greatest advantages for living in Forrest was the pristine natural environment (SDG 15, the *Biodiversity* model component), 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 model components are often indirect and this is made explicit in the feedback loops in Figure 5. This is one of the great strengths of system dynamics modelling, uniquely enabling the comprehensive modelling 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 model co-design 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-design process aided in the identification of these synergies and trade-offs with the detailed explanations provided by stakeholders of the way in which the model components were interconnected. Table 1 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.

## 4.4. Innovation and contribution

This work aimed to fill the research gap that exists between global, multisectoral systems models (such as FeliX (Rydzak et al., 2010) or En-ROADS (Kapmeier et al., 2021)), and smaller sectoral models which are applied to case studies. We co-designed the local SDGs systems model with the case study community and the result was a local scale multisectoral model. As part of the co-design process, we asked the community to focus on the interconnections between sectors in the model, and this resulted in a more enhanced understanding of where potential interventions may exist in the system to enable transition 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 integrated assessment modelling. We reiterate here that the co-design process facilitated this understanding so engaging with stakeholders, at all scales, should be considered.

The second key insight that we observed was the way in which the co-design 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 understanding for socio-ecological 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, it should be recognised that using co-design practices to design models can assist with achieving this goal.

## 4.5. Limitations, implications and future work

One of the drawbacks to complex modelling is its intensive development time. It can take many months to develop a single model. For small communities or resource-limited local authorities, this might be seen as a significant shortcoming; although a recent study by Di Lucia et al., (2021) found that the 'ease of use' of system dynamics models for SDG analysis (which includes development time) was seen as superior to coupled component models by model developers but not decision-makers. We suggest that using our technique of repurposing and adapting existing model structures may alleviate this somewhat. The increasing use of system dynamics modelling in this context may increase the number of existing models available which could be repurposed in this manner. There is also a need for groups of sectoral modellers to collaborate and produce multisectoral models for sustainability at the local scale that are generalisable across study areas.

The cultural burning structure within the model was included with the understanding that the science around the long-term effects of cultural burning is still underdeveloped. There is high uncertainty around its quantitative effects within the model, but both palaeoecological evidence and storytelling show that Indigenous Australians successfully managed the landscape using fire for tens of thousands of years. Including cultural burning within the model was important for us for a number of reasons: the Victorian state government has launched a formal policy to enable this (The Victorian Traditional Owner Cultural Fire Knowledge Group, 2021) so it is a practice which will be operating in the near future; a desire for increased cultural connection with Traditional Owners was a strong desire of the community in Forrest; and this was a tangible outcome of attempting to decolonise our work (Gram-Hanssen et al., 2021; Maclean et al., 2021).

This paper describes the local SDG systems model co-designed with the community in Forrest and our group model building process, and we have illustrated its application via a business-as-usual scenario. However, this is merely the first part of applying and examining the capabilities of the model. In future work we hope to analyse scenarios with the local SDG systems model and find locally specific pathways to sustainability. For example, we defined qualitative scenarios based upon the shared socioeconomic pathways (SSPs, O'Neill et al., 2017) and representative concentration pathways (RCPs, van Vuuren et al., 2011), but translated to a sustainability context. This model can be used as a simulation engine to test and quantify those scenarios (Szetey et al., 2021a). As referred to in section 3.2.3, there are several clear intervention points 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 present within the model which can make further differences, 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

In this work we have described the co-development of a local-scale system dynamics model for sustainability achievement through the SDGs. We combined techniques for group model building with a sustainability lens and this resulted in a much stronger focus on societal factors and social SDGs than was originally built into the model. These societal and human elements have, until recently, not been a key feature of complex, multisectoral models. Their emerging inclusion means that model construction is more challenging, however the outcome is a more complete and well-rounded model, particularly when considering human-natural systems. Social issues tend to be localised, which is one reason why local-scale modelling 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 mature modelling techniques (multisectoral system dynamics modelling) to a local-scale application using a co-design 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 generally for those who conduct multisectoral modelling which hopes to model societal factors. More broadly, it is beneficial for modelling sustainability issues which, by definition, include a social dimension.

# 6. 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

Allen C, Metternicht G, Weidmann T. 2016. National pathways to the Sustainable Development Goals (SDGs): A comparative review of scenario modelling tools. *Environ Sci Policy* **66**: 199–207. doi: 10.1016/j.envsci.2016.09.008

Allen C, Metternicht G, Weidmann T, Pedercini M. 2019. Greater gains for Australia by tackling all SDGs but the last steps will be the most challenging. *Nature Sustainability* **2**(11): 1041–1050. doi: 10.1038/s41893-019-0409-9

Andrews R, Turner D. 2006. Modelling the Impact of Community Engagement on Local Democracy. *Local Economy* **21**(4): 378–390. doi: 10.1080/02690940600951956

Angulo D, Angulo F, Olivar G. 2015. Dynamics and Forecast in a Simple Model of Sustainable Development for Rural Populations. *Bulletin of Mathematical Biology* **77**(2): 368–389. doi: 10.1007/s11538-014-9934-x

Australian Bureau of Statistics. 2017. Find Census Data. Find Census Data. Available at https://www.abs.gov.au/census/find-census-data.

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

Barbier EB, Burgess JC. 2017. The Sustainable Development Goals and the systems approach to sustainability. *Economics* **11**: 22. doi: 10.5018/economics-ejournal.ja.2017-28

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

Bastan M, Ramazani Khorshid-Doust R, Ahmadvand A, Delshad Sisi S. 2018. Sustainable development of agriculture: a system dynamics model. *Kybernetes* **47**(1): 142–162. doi: 10.1108/K-01-2017-0003

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

Bodorkós B, Pataki G. 2009. Local communities empowered to plan?: Applying PAR to establish democratic communicative spaces for sustainable rural development. *Action Research* **7**(3): 313–334. doi: 10.1177/1476750309336720

Brody SD, Godschalk DR, Burby RJ. 2003. Mandating Citizen Participation in Plan Making: Six Strategic Planning Choices. *Journal of the American Planning Association* **69**(3): 245–264. doi: 10.1080/01944360308978018

Burby RJ. 2003. Making Plans that Matter: Citizen Involvement and Government Action. *Journal of the American Planning Association* **69**(1): 33–49. doi: 10.1080/01944360308976292

Bureau of Meteorology. 2021. Climate Data Online. Climate Data Online. Available at http://www.bom.gov.au/climate/data/.

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

Campolongo F, Cariboni J, Saltelli A. 2007. An effective screening design for sensitivity analysis of large models. *Environmental Modelling & Software* **22**(10): 1509–1518. doi: 10.1016/j.envsoft.2006.10.004

Cavicchi B. 2018. The burden of sustainability: Limits to sustainable bioenergy development in Norway. *Energy Policy* **119**: 585–599. doi: 10.1016/j.enpol.2018.05.015

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

Collins RD, de Neufville R, Claro J, Oliveira T, Pacheco AP. 2013. Forest fire management to avoid unintended consequences: A case study of Portugal using system dynamics. *Journal of Environmental Management* **130**: 1–9. doi: 10.1016/j.jenvman.2013.08.033

Collste D, Pedercini M, Cornell SE. 2017. Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies. *Sustainability Science*(6): 921. doi: 10.1007/s11625-017-0457-x

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

CSIRO. 2021. Latest Cape Grim greenhouse gas data. CSIRO. Available at https://www.csiro.au/en/research/natural-environment/atmosphere/latest-greenhouse-gas-data. Accessed 2022 Jan 20.

DELWP. 2021. VicClim dataset 1972-2020. Victorian Government.

Di Lucia L, Slade R, Khan J. 2021 Dec 6. Decision-making fitness of methods to understand Sustainable Development Goal interactions. *Nat Sustain*: 1–8. doi: 10.1038/s41893-021-00819-y

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, Zimmermann N, Carnohan S, Davies M. 2018. Participatory system dynamics modelling for housing, energy and wellbeing interactions. *Building Research & Information* **46**(7): 738–754. doi: 10.1080/09613218.2017.1362919

Elsawah S, Mclucas A, Mazanov J. 2009. Modeling water resource in the Australian Capital Territory: Knowledge elicitation for system dynamics model building. Anderssen, RS and Braddock, RD and Newham, LTH, editor. 18TH WORLD IMACS CONGRESS AND MODSIM09 INTERNATIONAL CONGRESS ON MODELLING AND SIMULATION: INTERFACING MODELLING AND SIMULATION WITH MATHEMATICAL AND COMPUTATIONAL SCIENCES: 3796–3802. NEDLANDS, WA, AUSTRALIA: UNIV WESTERN AUSTRALIA.

Fallah-Fini S, Triantis K, Rahmandad H, de la Garza JM. 2015. Measuring dynamic efficiency of highway maintenance operations. *Omega* **50**: 18–28. doi: 10.1016/j.omega.2014.07.001

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

Forrester JW. 2007. System dynamics—a personal view of the first fifty years. *System Dynamics Review* **23**(2–3): 345–358. doi: 10.1002/sdr.382

Gao L, Bryan BA. 2016. Incorporating deep uncertainty into the elementary effects method for robust global sensitivity analysis. *Ecological Modelling* **321**: 1–9. doi: 10.1016/j.ecolmodel.2015.10.016

Gao L, Bryan BA. 2017. Finding pathways to national-scale land-sector sustainability. *Nature* **544**(7649): 217-+. doi: 10.1038/nature21694

Gram-Hanssen I, Schafenacker N, Bentz J. 2021 May 7. Decolonizing transformations through 'right relations.' *Sustainability Science*, in press. doi: 10.1007/s11625-021-00960-9

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.

IPBES. 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES secretariat. Available at https://doi.org/10.5281/zenodo.3831673.

Kapmeier F, Sterman J, Siegel L, Eker S, Fiddaman T, Homer J, Rooney-Varga J, Jones A. 2021. En-ROADS: A Global Energy and Climate Simulator to Support Strategic Thinking and Public Outreach. 2021 Apr 1. EGU General Assembly Conference Abstracts. Available at https://ui.adsabs.harvard.edu/abs/2021EGUGA..23.7608K.

Kimmich C, Gallagher L, Kopainsky B, Dubois M, Sovann C, Buth C, Bréthaut C. 2019. Participatory Modeling Updates Expectations for Individuals and Groups, Catalyzing Behavior Change and Collective Action in Water-Energy-Food Nexus Governance. *Earth's Future* **7**(12): 1337–1352. doi: 10.1029/2019EF001311

Kok KPW, Gjefsen MD, Regeer BJ, Broerse JEW. 2021 Sep 13. Unraveling the politics of 'doing inclusion' in transdisciplinarity for sustainable transformation. *Sustain Sci*, in press. doi: 10.1007/s11625-021-01033-7

Kwakkel J. 2019. *Ema_workbench Python Package*.

Maclean K, Woodward E, Jarvis D, Turpin G, Rowland D, Rist P. 2021 May 27. Decolonising knowledge co-production: examining the role of positionality and partnerships to support Indigenous-led bush product enterprises in northern Australia. *Sustainability Science*, in press. doi: 10.1007/s11625-021-00973-4

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*: 1–27. 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

Nabavi E, Daniell KA, Najafi H. 2017. Boundary matters: the potential of system dynamics to support sustainability? *Journal of Cleaner Production* **140**(Part 1): 312–323.

Navarro A, Tapiador FJ. 2019. RUSEM: A numerical model for policymaking and climate applications. *Ecological Economics* **165**: 106403. doi: 10.1016/j.ecolecon.2019.106403

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

O'Neill BC, Kriegel E, Ebi K, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven B, Van Vuuren D, Birkmann J, Kok K, et al. 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*: 169. doi: 10.1016/j.gloenvcha.2015.01.004

Papachristos G. 2011. A system dynamics model of socio-technical regime transitions. *Environmental Innovation and Societal Transitions* **1**(2): 202–233. doi: 10.1016/j.eist.2011.10.001

Papachristos G. 2019. System dynamics modelling and simulation for sociotechnical transitions research. *Environmental Innovation and Societal Transitions* **31**: 248–261. doi: 10.1016/j.eist.2018.10.001

Pedercini M, Arquitt S, Chan D. 2020. Integrated simulation for the 2030 agenda†. *System Dynamics Review* **36**(3): 333–357. doi: 10.1002/sdr.1665

Philippidis G, Shutes L, M'Barek R, Ronzon T, Tabeau A, van Meijl H. 2020. Snakes and ladders: World development pathways' synergies and trade-offs through the lens of the Sustainable Development Goals. *Journal of Cleaner Production* **267**: 122147. doi: 10.1016/j.jclepro.2020.122147

Rahmandad H, Sterman JD. 2012. Reporting guidelines for simulation-based research in social sciences. *System Dynamics Review* **28**(4): 396–411. doi: 10.1002/sdr.1481

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. 2008. Stakeholder participation for environmental management: A literature review. *Biological Conservation* **141**(10): 2417–2431.

Rydzak F, Obersteiner M, Kraxner F. 2010. Impact of Global Earth Observation - Systemic view across GEOSS societal benefit area. *International Journal of Spatial Data Infrastructures Research*: 216–243. doi: 10.2902/1725-0463.2010.05.art9

Rydzak F, Obersteiner M, Kraxner F, Fritz S, McCallum I. 2013. FeliX3 – Impact Assessment Model Systemic view across Societal Benefit Areas beyond Global Earth Observation. Austria: IIASA. Model Report and Technical Documentation. Available at https://github.com/iiasa/Felix-Model/blob/master/Felix3_ModelReport.pdf.

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

Sterling EJ, Zellner M, Jenni KE, Leong K, Glynn PD, BenDor TK, Bommel P, Hubacek K, Jetter AJ, Jordan R, et al. 2019. Try, try again: Lessons learned from success and failure in participatory modeling. Kapuscinski AR, Locke KA, Borsuk M, editors. *Elementa: Science of the Anthropocene* **7**: 9. doi: 10.1525/elementa.347

Sterman JD. 2001a. System Dynamics Modeling: Tools for Learning in a Complex World. *California Management Review* **43**(4): 8–25. SAGE Publications Inc. doi: 10.2307/41166098

Sterman JD. 2001b. *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

Tenza A, Perez I, Martinez-Fernandez J, Gimenez A. 2017. Understanding the decline and resilience loss of a long-lived socialecological system: insights from system dynamics. *Ecol Soc* **22**(2): 23. doi: 10.5751/es-09176-220215

The Victorian Traditional Owner Cultural Fire Knowledge Group. 2021. The Victorian Traditional Owner Cultural Fire Strategy. Victoria, Australia: DEWLP. Available at https://knowledge.aidr.org.au/media/6817/fireplusstrategyplusfinal.pdf. Accessed 2021 Dec 15.

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

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.

Vennix JAM. 1996. *Group Model Building : Facilitating Team Learning Using System Dynamics.* J. Wiley. Available at https://search.ebscohost.com/login.aspx?direct=true&db=cat00097a&AN=deakin.b2360071&site=eds-live&scope=site.

Ventana Systems I. 2021. *Vensim DSS*. Ventana Systems Inc. Available at https://vensim.com/.

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, Bousquet F. 2010. Modelling with stakeholders. *Environmental Modelling & Software* **25**(11): 1268–1281. doi: 10.1016/j.envsoft.2010.03.007

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

Voinov A, Kolagani N, McCall MK, Glynn PD, Kragt ME, Ostermann FO, Pierce SA, Ramu P. 2016. Modelling with stakeholders – Next generation. *Environmental Modelling & Software* **77**: 196–220. doi: https://doi.org/10.1016/j.envsoft.2015.11.016

Voinov A, Seppelt R, Reis S, Nabel JEMS, Shokravi S. 2014. Values in socio-environmental modelling: Persuasion for action or excuse for inaction. *Environmental Modelling & Software* **53**: 207–212. doi: 10.1016/j.envsoft.2013.12.005

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

van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque J-F, et al. 2011. The representative concentration pathways: an overview. *Climatic Change* **109**(1): 5. doi: 10.1007/s10584-011-0148-z

Zhang Q, Prouty C, Zimmerman JB, Mihelcic JR. 2016. More than Target 6.3: A Systems Approach to Rethinking Sustainable Development Goals in a Resource-Scarce World. *Engineering* **2**(4): 481–489. doi: 10.1016/J.ENG.2016.04.010

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