The impacts of climate change on structurally interconnected social-ecological systems: using integrated spatial modelling to assess beehive migration patterns in Western Australia

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THESIS DECLARATION

I, Vidushi Amit Patel, certify that:

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ABSTRACT

Beekeeping represents a unique social-ecological system (SES) where bees, humans, and forage landscapes interact to provide a range of ecosystem services. The decline in global bee stocks due to complex natural and anthropogenic drivers is impacting bee system contributions that ultimately support sustainable development. Managing these natural and anthropogenic pressures requires a systems approach to understand how pressures manifest within the system. The bee industry as a socio-ecological system has been relatively unexplored to date, with even fewer examples of integrated models that allow for the examination of pressures on the sustainability of this unique industry.

To address this gap, this thesis presents a social-ecological characterisation of the beekeeping system using Elinor Ostrom's social-ecological systems framework, and develops an integrated modelling approach, the *B-Agent,* to assess the impacts of climate pressures on the Western Australian (WA) beekeeping SES. Serving as a roadmap for the development of bee-human system solutions, this research addresses four objectives: i) develop an understanding of the interconnections between bees and people, in the context of the Sustainable Development Goals (SDGs), ii) through the lens of social-ecological systems thinking, characterise the elements, patterns, processes, and feedbacks of a commercial honey production system as well as the pressures acting on the system, iii) identify spatial patterns of forage-availability under future climate scenarios in WA, and iv) develop an agent-based model representing the beehive migration process to examine how changes in forage-availability will effect spatial patterns of beehive migration. A system perspective was used to address the first two objectives, specifically, a social-ecological systems framework was used to facilitate an understanding of the structural interconnectivities between social and ecological elements of commercial honey production in WA, and to identify the biophysical and anthropogenic pressures acting on the system. To address objectives three and four, an integrated spatial modelling framework, the *B-Agent* is presented,

integrating multiple stakeholder engagement approaches, species distribution modelling, and an agent-based model to simulate a key social-ecological interaction – beehive migration.

More specifically, a novel assessment of the critical contributions bees make to our planet's future sustainable development is presented, with examples drawn from a variety of case studies to highlight the potential contribution of bees to 15 of the 17 United Nations Sustainable Development Goals (SDGs) and at least 30 SDG targets. In addition to addressing the first research objective, this study emphasised the need for using a system approach to understand interconnectivities within the coupled bee-human system, and identified eight thematic priority areas for further investigation into bee-human relationships.

To further investigate the bee-human system, the first application of Elinor Ostrom's social-ecological system (SES) framework to the beekeeping industry, addressing the second objective, is presented. To describe the beekeeping industry, 163 SES variables outlining system elements, key patterns of interaction, and critical pressures emerging from SES interconnectivities were identified using literature and iterative stakeholder engagement. Here, results indicate the need for new modelling approaches to inform resource management decisions ensuring effective pollination and long-term apiary production.

To address this need, the *B-Agent* model was developed to examine the impact of climate change on the beekeeping SES. The B-Agent model represents an agent-based model developed through a series of stakeholder interviews to identify key forage species targeted by WA apiarists for honey production. A species distribution model (SDM), *Maxent*, was then used to model the distribution of key flora now and under a future climate scenario. SDMs for individual species were then attributed with associated flowering times to map the distribution of monthly forage availability across the southwest of WA. Finally, monthly forage availability maps were integrated with an

agent-based model (ABM) representing the spatial decision-making process of migratory commercial beekeepers to examine the impacts of changes in forage availability on spatial migration patterns.

Species distribution modelling results highlight the effects of climate change on individual forage species, where over half of key flora identified by beekeepers will lose portions of their current geographic range with a trend in lateral and poleward expansion. The impact of changes to bee forage distributions was reflected in changes to future beehive migration patterns resulting from the ABM, indicating an increase in beekeeper travel distance in the moderate emission future climate scenario and an eastward shift in future apiary forage locations.

The *B-Agent* approach provides an evidence base to explain the structural interconnectivities between forage landscapes and beehive migration decisions. By modelling the impact of climate change on forage availability, this research highlights the importance of tools and approaches for informing management decisions that ensure the sustainability of beekeeping. Results from *B-Agent* model runs show that the spatial distribution of key bee forage species are changing, which is causing a shift in species flowering richness and availability of premium forage species and will lead to shifting spatial patterns of hive site use. Through a representation of the structural interconnectivity between forage environments and beehive migration decisions, *B-Agent* provides a framework for examining the likely impacts of both biophysical and anthropogenic pressures on the spatial patterns of beehive migration relative to variations in the state of forage availability in the future.

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AUTHORSHIP DECLARATION: CO-AUTHORED PUBLICATIONS

This thesis is divided into seven chapters, four of which (Chapters 3, 4, 5 and 6) contain manuscripts that have been published or submitted for publication in peer-reviewed journals. All three manuscripts are co-authored with my supervisors (i.e., Dr. Bryan Boruff, Dr. Eloise Biggs, and Dr. Natasha Pauli), one with the CEO of CRC for honeybee products (Dr. Liz Barbour) and one with my fellow PhD candidate (Daniel Dixon). As the first and corresponding author, I completed a significant portion of the research and independently drafted all co-authored manuscripts included in this thesis. During the research, the co-authors (i.e., Dr. Bryan Boruff, Dr. Eloise Biggs and Dr. Natasha Pauli) provided supervision and advice, as well as assistance with language editing for the drafted manuscripts. Dr Bryan Boruff and Dr. Liz Barbour also provided financial support for the research. The bibliographical details of the work, where it appears in the thesis, and authorship contributions are listed below. I have obtained permission from all co-authors to include their work in my thesis.

This thesis contains the following co-authored work that has been published or submitted for publication:

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Date: 19 April 2023

I, Dr. Bryan Boruff certify that the student's statements regarding their contribution to each of the works listed above are correct.

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Date: **10 April 2023**

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Chapter 1. Introduction

Recent global change is attributed to the complex interplay between people and the planet at multiple spatial and temporal scales (Homer-Dixon et al., 2015). Recognising interconnections and dynamics between people and the planet is critical for addressing challenges related to global change (Fischer et al., 2015; Ives et al., 2017; Turner II et al., 2016). Livelihood activities that rely on the availability of common resources present an interesting subset of interconnections and interdependence between people and nature. Specifically, primary producers are already experiencing the effects of land use and climate change. Integrating the rich local knowledge of these producers through a holistic understanding and scientific modelling framework provides an opportunity to capture multiple dimensions of human and natural systems in order to assess the impacts of global change.

The impacts of global change on beekeeping has been highlighted in recent research (Galbraith et al., 2017; Giannini et al., 2017). Of 20,000 globally described bee species, fifty bee species are managed by people, of which approximately 12 are managed for crop pollination (Potts et al., 2016a). The European Honeybee (*Apis mellifera)* is a widely managed species for pollinating many crops and wild plants (Hung et al., 2018; Saunders et al., 2018) and obtaining multiple commercially and medicinally valuable products (e.g., honey, wax, propolis, royal jelly) (Easton-Calabria et al., 2019; Pasupuleti et al., 2017). Beekeeping operates on a migratory (i.e., moving beehives across a sequence of forage sites) and non-migratory (i.e., keeping beehive stationary on forage sites) basis. As such, beekeeping presents interconnections between social and ecological systems. This unique intertwined bee-human system is facing a number of change-related challenges impacting bee populations and beekeepers. Western Australian migratory beekeeping is a special case due to geographic isolation, which provides a specific boundary to systematically examine the bee-human relationship.

To this end, this thesis presents a systems approach to unpacking the social-ecological character of bee-human systems by: first, providing a novel understanding of the role of the bee-human relationship within the broader context of sustainable development; second, presenting the first social-ecological characterization of beekeeping systems; and finally, developing a novel integrated modelling approach presenting beehive migration process to present a case study of the impacts of climate change on the Western Australian beekeeping system. Beekeeping is an important activity contributing towards sustainable development. Interactions within the migratory beekeeping system are complex and impacted by multiple pressures, which requires an application of systems thinking to ensure viable beekeeping systems into the future.

The remainder of this chapter provides an overview of the systems approach used in the research (i.e., complex adaptive systems) as well as the importance of social-ecological systems in sustainable development. Next, existing knowledge of the social-ecological understanding of bee-human systems is discussed, followed by potential modelling approaches for examining the systems interconnectivities. The chapter concludes by stating the thesis objectives and research questions, including a short description of the structure of the thesis.

1.1 Approaches for understanding complex adaptive systems

1.1.1 Complex systems

A system is a unified entity composed of interconnected components that exhibit unique properties attributed to any of the individual components that comprise the unified entity (Merali & Allen, 2011). A system is complex when the components interact in a linear or non-linear fashion, resulting in emergent behaviours at the system level (Newman, 2011). Complex systems are dynamic systems that continuously interact with their environment; show *path dependence* (i.e., the current and future state of the system follows the path of the previous state) and are nested with various levels of organizations (Rotmans & Loorbach, 2009). Some classic examples of complex systems include climate systems, the human brain, eusocial insects (e.g., ants, termites, and honeybees), economic systems and human society (Ladyman & Wiesner, 2020). When the components in a complex system continuously adapt according to existing and anticipated surroundings, it is called a complex adaptive system (Holland, 1992), in which relatively simple rules of interaction results in complex, emergent behavioural patterns (Carmichael & Hadžikadić, 2019).

1.1.2 Social-ecological systems (SES)

Social-ecological systems are widely recognized as complex adaptive systems (Levin et al., 2013; Preiser et al., 2018). The concept of social-ecological systems presents an integrated perspective of humans, nature, and their interactions (Berkes & Folke, 1998; Ostrom, 2009). SES interactions are driven by a range of ecological and/or socioeconomic processes and contribute to SES dynamics in response to change (Chapin et al., 2009). Integration of these social and ecological processes in an SES primarily adheres to the notion of resilience and involves the application of transdisciplinary approaches (Virapongse et al., 2016). SES resilience refers to the ability of the system to sustain its identity under the effect of internal change and external perturbations (Cumming & Cumming, 2011). The changes affecting SES are multifaceted, which often requires employing a combination of methods that can capture components of social and ecological processes while also capturing complex interconnectivities among them (de Vos et al., 2019).

1.1.3 Modelling complex SES interconnectivities

Humans, the environment, and their complex interconnectivities are embedded in an SES (Biggs et al., 2021; Ostrom, 2009). The primary goal for modelling SES interactions is to inform sustainable resource management initiatives by addressing the impacts of stressors on the system (McGinnis & Ostrom, 2014; Rodela et al., 2019). Here, modelling system interactions illustrates how changes to these interactions result in new and emerging patterns in the system (Schlüter et al., 2019).

Furthermore, SESs are 'open' systems that interact with other systems (Biggs et al., 2021). As a result, a change in one SES's behaviour may cascade to other interconnected SESs, magnifying or attenuating interactions across the systems (Homer-Dixon et al., 2015). Overall, SES dynamics are challenging to predict, especially in light of global change, which requires methods that can integrate diverse data types (e.g., qualitative and quantitative) often obtained from multiple sources (Zvoleff & An, 2014).

Integrated modelling provides an approach for investigating interactions and the effects of natural or anthropogenic stressors by coupling different models either though shared inputs or by treating the output of one submodel as the input for another (Hamilton et al., 2015). For example, in a study of a shallow lake in Martin and Schlüter (2015) integrated a System Dynamics Model with an Agent-Based Model (ABM) to analyse interactions between ecological dynamics (i.e., nutrient dynamics in the lake) and micro-level human actions (i.e., an individual house owner’s willingness to upgrade on-site sewage systems that contribute to nutrient flow into the lake). Their approach enabled an improved understanding of SES complexity associated with aquatic restoration.

1.2 Social-ecological systems approach for sustainable development

Achieving development while protecting the resource base is one of the most pressing global challenges and is the focus of the Sustainable Development Goals (SDGs), proposed by the United Nations. The biosphere forms the foundation for the SDGs (Folke et al., 2016; Leal Filho et al., 2018; Rockström & Sukhdev, 2016). Social-ecological systems operate within and depend on the Biosphere (Folke et al., 2016). Recognition of this intertwinedness resulted in a surge of research focusing on integrating an SES approach with the SDGs and similar global sustainability initiatives (de Vos et al., 2019; Leal Filho et al., 2018; Reyers & Selig, 2020). Such an integration often results in complex outputs, e.g., SES-SDG links outlined in long multi-page tables (e.g., Leal Filho et al. (2018); Selomane et al. (2019)) or links presented within a complicated diagram (e.g., Lim et al.

(2018)), which may not be appealing to decision-makers who prefer clear information and recommendations.

A collection of place-based case studies can help localise sustainability initiatives by integrating local knowledge, identifying social-ecological feedback and addressing the local level impacts of global challenges (Martín-López et al., 2020; Tan et al., 2019). Furthermore, because the SDGs are well-known among decision-makers and the general public, a place-based understanding of how a particular organism, social behaviour or an interaction between the two, may contribute to achieving the SDGs and raise awareness of the existing social-ecological context. For example, understanding the contribution of insects towards SDGs has supported a shift in perceptions of insects from enemies or allies to ecosystem service providers (Dangles & Casas, 2019). Such awareness about strong connections between people and nature can potentially transform the way humans interact with their environment and may lead to more ethical use of natural resources (Ives et al., 2017).

1.3 Social-ecological view of bee-human systems and sustainable development

There is increasing discussion around bee-human relationships and associated contributions to the ecological system and society in recent research (Dangles & Casas, 2019; Klein et al., 2018). Recent reports of decline in bee populations are threatening this bee-human relationship (Potts et al., 2016b). Declining populations of wild bee pollinators (Biesmeijer et al., 2006; Koh et al., 2016) and the number of managed bee colonies (Potts et al., 2010a) have been observed in Europe and North America and are likely to have occurred elsewhere (Goulson et al., 2015). Global decline in the number of bee species is also reported by Zattara and Aizen (2021). With these reports on bee decline, there has been a surge of research focusing on the drivers of bee decline and ways to support bee populations, particularly to sustain the range of services they provide for humans and nature (Decourtye et al., 2019; Gill et al., 2016; Potts et al., 2016b).

Bees and humans have a long-standing relationship that dates back to the Neolithic period (Roffet-Salque et al., 2015). However, research exploring the mutualistic bee-human relationship is primarily focused on the contribution of people to declining bee populations. For example, market-driven land use change (e.g., converting conservation lands to intensive cropping) has limited bee access to forage resources and exposed bees to agrochemicals in the name of increased food production (Durant, 2019). Nonetheless, people are integral to bee functionality through the facilitation of access to forage resources, management of disease, and the development of bee-friendly policies (Potts et al., 2016a; Veldtman, 2018). This reciprocal relationship is critical to understanding these interactions within a systematic framework. As such, a comprehensive understanding of these interdependencies within the well-known SDG context can increase awareness and improve community participation in land management initiatives aiming for pollinator conservation such as agricultural diversification and urban greening (Schönfelder & Bogner, 2017; Senapathi et al., 2015).

1.4 Beekeeping – A social ecological system

Beekeeping represents a unique mutually beneficial bee-human relationship that is increasingly recognised for its role in sustainable development (Vinci et al., 2018). Beekeeping (e.g., bee industry or apiculture) is an economic activity that generates profits from natural resources while also providing environmental and sociocultural benefits (Etxegarai-Legarreta & Sanchez-Famoso, 2022). The key relationship in the beekeeping system is the association between bees and foraging grounds, where beekeepers facilitate access to quality forage by keeping beehives stationary or migrating them to landscapes with diverse pollen and nectar sources, supporting a nutritious diet and enhanced disease immunity (Goulson et al., 2015).

Migratory beekeeping practices involves transporting large numbers of beehives to the flowering sites for honey production and crop pollination. The sustainability of migratory beekeeping depends on continuous access to a sequence of forage sites (Pilati & Prestamburgo, 2016). As such, bee foraging represents a landscape scale process, where landscape composition is important for a colony's success (Sponsler & Johnson, 2015). Yet, the extent to which changes in forage landscape in the future will affect bees and beekeeping is largely unknown (Vanbergen & Initiative, 2013).

Changes in forage landscapes contributes to the majority of stressors impacting beekeeping systems around the world. The spatially explicit and intertwined nature of these stressors demands a systems approach to manage the impacts on beekeeping systems. For example, using a SES approach to understand the impacts of land use change on migratory beekeeping in Uruguay has revealed that land use change has undermined the resilience of beekeeping livelihoods by introducing additional expenses and challenges to honey production (Malkamäki et al., 2016). While such qualitative inquiries highlight important feedback between forage landscapes and beekeeping success, it also calls for improved understanding of beekeeping SES as well as a quantitative examination of the SES pressures impacting beekeeping systems.

1.4.1 Overview of stressors on migratory beekeeping systems

Extensive loss of honeybee colonies has been reported over the past several decades, which may severely impact biodiversity and associated ecosystem services (Nazzi & Pennacchio, 2014; Potts et al., 2010a). The number of managed bee colonies decreased by 25% in Central Europe from 1985 to 2005 and by approximately 50% in North America since the 1940s (Goulson et al., 2015). This widespread loss has been attributed to the combined effects of pesticides, parasites, reduced access to forage, and climate change (Goulson et al., 2015; Nazzi & Pennacchio, 2014; Potts et al., 2010b; Wagner, 2020).

The availability of adequate bee pasture (forage grounds) has an impact on both beekeeping profitability and bee health (vanEngelsdorp & Meixner, 2010). Stress from inadequate forage resources can lead to nutritional imbalances in bees and increased susceptibility to disease (Smart et al., 2016; vanEngelsdorp & Meixner, 2010). Beekeeping, unlike agriculture, does not require land ownership (Hilmi Martin et al., 2011), however production is determined by access to quality forage and the management practices that affect the foraging landscapes accessed by beekeepers (Dixon et al., 2021; Galbraith et al., 2017). Migratory beekeepers access forage resources occurring on government or privately owned land, which depends on permission from authorities or through negotiation with private landowners (Hill et al., 2019). Moreover, forage sites often show spatial overlap with other land tenure types, which may result in additional negotiation with existing lease owners (Salvin, 2015), further adding a multifunctional aspect to resource management for beekeeping.

Composition of forage landscapes plays an important role in the health of bee colonies (Sponsler & Johnson, 2015). Foraging on agricultural lands can have significant impacts on bee health. Agrochemicals can suppress bee immunity and increase risk to pests and pathogens such as the mite *Varroa destructor* (Sánchez-Bayo et al., 2016), which is also a vector for pathogens such as DWV (Deformed wing virus) often linked to reduced life span and potential large scale colony loss (Potts et al., 2010a; vanEngelsdorp & Meixner, 2010). Parasites and pathogens also affect bee cognition by altering foraging performance, visuo-spatial learning and memory of their host bees, which eventually affect brood development and colony survival (Gomez-Moracho et al., 2017). Exposure to pesticides at developmental stages, can impair bees' ability to locate floral resources which exacerbates nutritional stress (Gill et al., 2016; Goulson et al., 2015).

The long-distance transport of bees for pollination services adds additional 'shipping' stress (Melicher et al., 2019) which may increase susceptibility to bacterial and viral infections, and ultimately colony loss. Long distance transport also contributes to the spread of honeybee parasites including *V. destructor*, which was originally associated with the Asian honeybee (*Apis cerana*) and is now prevalent in European honeybee (*A. mellifera*) hives in many parts of the world (Alger et al., 2018; Goulson et al., 2015). Additionally, transporting colonies over longer distances is fuel intensive, which further increases the carbon footprint of honey production (Pignagnoli et al., 2021) and may affect the overall profitability of beekeepers. Moreover, long distance travel could also have social impacts on individual beekeepers' wellbeing (e.g., fatigue, isolation, experience of darkness and other site conditions (Phillips, 2014)), all of which have received less scholarly attention.

A changing climate exacerbates the above stressors by impacting various ecological and social-economic aspects of beekeeping systems (Flores et al., 2019; Goulson et al., 2015). Climate change impacts on honeybee behaviour, physiology, and distribution (Le Conte & Navajas, 2008), influences flower development, and nectar and pollen production, which are directly linked with colonies' foraging activity and development. A drying climate, including periods of drought will reduce nectar in flowers, and can also reduce the abundance and variety of pollen which can lead to starvation, weakened immunity, and increased susceptibility to pathogens in honeybees (Abou-Shaara, 2015; Le Conte & Navajas, 2008). A positive correlation between rainfall and winter survival of bee colonies (Switanek et al. 2017) and honey harvest (Delgado et al. 2012) has been noted in the literature. Honeybee foraging activity is strongly dependent on temperature, solar radiation, and wind direction and speed. A changing climate may disrupt foraging activity, spatial-temporal mobility patterns, and associated honey production from beehives (Castellanos-Potenciano et al., 2017; Delgado et al., 2012). Furthermore, potential range shift in the distribution of suitable habitat for managed bee species due to climate change is also reported in recent studies (Giannini et al., 2020; Koch et al., 2019; Lima & Marchioro, 2021). A similar examination (i.e., potential range shift in the distribution of forage species) could provide important insights into the potential changes in the patterns of migratory beekeeping.

1.4.2 Developing a system approach for addressing beekeeping stressors

Multiple co-occurring stressors are affecting honeybee populations (Goulson et al., 2015; Steinhauer et al., 2018; Wagner, 2020), and requires the application of a systems approach to support bee conservation and landscape management (Becher et al., 2013). Over the last decade, significant progress has been made in using a systems approach to understand these impacts on bees; for example, the BEEHAVE model (Becher et al., 2014) and various applications (Becher et al., 2018; Horn et al., 2016), have been used to assess the impacts of stressors on individual bees, bee colonies, and the broader natural community. BEEHAVE is an agent-based model (ABM) simulating colony level dynamics, *Varroa* mite populations, epidemiology of *Varroa*-transmitted viruses, and bee foragers' activities in a spatially explicit landscape. While much of this research focuses directly on bee-forage landscape interactions, the connections between beekeepers, bees and forage have received less attention. There is a growing body of research that highlights the importance of humans in supporting the contributions of bees in human-mediated landscapes, emphasizing the interaction between bees and humans as a reciprocal relationship (Potts et al., 2016a; Veldtman, 2018). However, employing a systems approach to examine the complexities of these relationships is still in its infancy.

In migratory honey production systems, the sustainability of apiary production depends on the quality and availability of a sequence of forage sites accessed by beekeepers (Pilati & Prestamburgo, 2016). Beekeepers' decisions for selecting an optimum sequencing of sites to maximise production and bee health, is based on knowledge of local forage resources (Galbraith et al., 2017; Pilati & Fontana, 2018). To this end, several modelling approaches have addressed various aspects of beekeeping. For example, colony responses to different disease management (i.e., *Varroa* mites, virus infection and acaricide treatment) scenarios in the BEEHAVE model (Becher et al., 2014); honey extraction and bee culling in a bioeconomic model of beekeeping (Champetier et al., 2014), and selection of profitable apiary sites in a microeconomic model of migratory beekeeping (Pilati & Fontana, 2018). While these modelling approaches highlight some aspects of beekeeping and provide important insights into managing bees within agriculture landscapes, none explicitly integrate the beekeepers' decision-making process. Furthermore, the management of beekeeping systems within natural landscapes, such as forests, is more complex due to the diversity of forage resources accessible to bees and beekeepers as well as the multifunctional nature of these forage landscapes.

1.5 Case study context

The state of Western Australia (WA) occupies the western third of the Australian continent. The beekeeping industry of WA is characterized by clean and healthy colonies of the European honeybee (*Apis mellifera*), free of pests and disease affecting bee populations in almost all other parts of the world (Chapman et al., 2008; Gordon et al., 2014). The WA beekeeping industry is heavily reliant on native flora, with production from native woodlands, healthlands and shrublands accounting for approximately 80-90% of the state's honey production (Arundel et al., 2016; Benecke, 2007). Key honey-producing landscapes in WA are geographically restricted to the southwest region of the state (Benecke, 2007; Gibbs & Muirhead, 1998; Smith, 1969). The southwest region of WA is one of the original 25 global biodiversity hotspots (Myers et al., 2000), and home to a great diversity of plant species, including high diversity in the plant families of Myrtaceae, Proteaceae and Ericaceae (Beard et al., 2000) are some of the most important families of bee forage species targeted in WA (Smith, 1969).

The WA commercial beekeeping industry (i.e., beekeepers with more than 50 hives) is a relatively small but rapidly growing migratory industry with 161 commercial beekeepers reported in 2019, which is just 5% of the total registered beekeepers including commercial and recreational beekeepers in WA (Clarke & Le Feuvre, 2021). The industry follows migratory practices and operates intrastate as a closed system due to strict regulations on bee importation and hive movement throughout the state (Crooks, 2008; RIRDC, 2015). Beekeepers access a sequence of flowering sites from government and privately owned land. Access to forage sites on private land is generally negotiated with individual landowners. However, placing beehives on government land requires beekeepers to obtain an apiary permit (Figure 1).

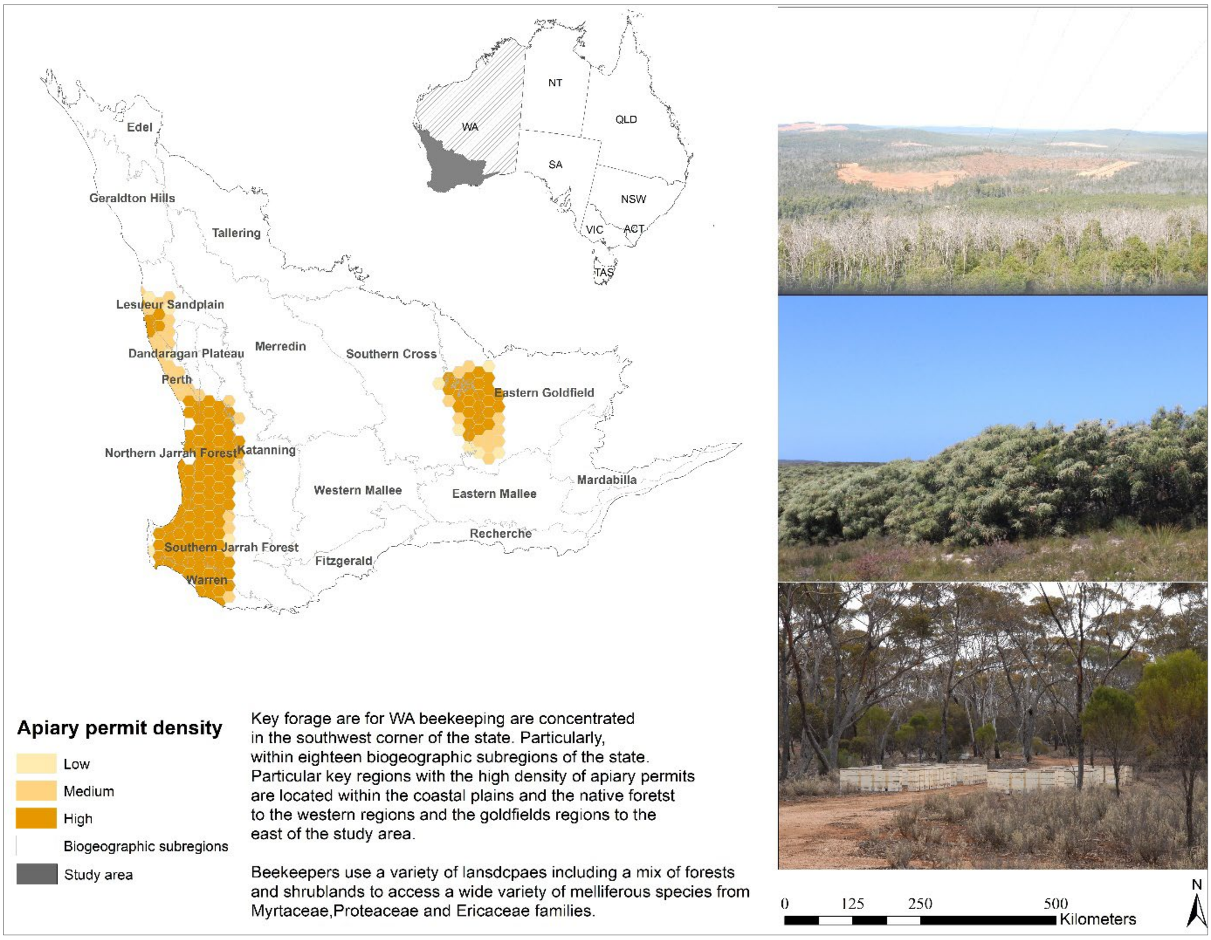

Figure 1: Key bee forage areas accessed by migratory beekeepers in Western Australia. Beekeepers place a load of beehives (approximately 100 beehives) on each apiary sites located on a variety of landscapes.

Beekeepers secure leases for apiary permits and migrate their beehives chasing flowering events (Gordon et al., 2014; Somerville & Nicholson, 2005). Often apiary permits spatially overlap with other land tenures (e.g., pastoral leases) requiring beekeepers to further negotiate access with other lease owners. In addition to accessing forage resources, the WA beekeeping industry is also facing multiple challenges to its finite resource base.

The southwest region (i.e., key forage area for WA, Figure 1) for WA beekeeping has undergone extensive land clearing for urban and agriculture expansion (Bradshaw, 2012). The region has reported almost 20% reduction in rainfall since the 1970s (Hughes, 2011; Makuei et al., 2013), particularly in autumn-winter rainfall (Andrys et al., 2017; Pettit et al., 2015). The rainfall variation is related to the variation in sea surface temperatures between the Indian and Pacific Oceans, leading to a southward shift in low pressure systems that contribute to regular winter rain (Bates et al., 2008; Scanlon & Doncon, 2020). Several studies have also attributed this declining rainfall to land clearing and other anthropogenic disturbances to the region (Andrich & Imberger, 2013; Cai & Cowan, 2006), and highlighted the potential impact on food production and resource availability for industrial growth (Dey et al., 2019; Hochman et al., 2017). A continued decline of rainfall, particularly across medium and high emission scenarios, is projected with high consensus among different climate models (Andrys et al., 2017; Hope et al., 2015). Reduction in precipitation coupled with increasing temperature has manifested in increased drought frequency (Andrys et al., 2017; Makuei et al., 2013) further impacting numerous plant species (Fitzpatrick et al., 2008; Hamer et al., 2015; Yates et al., 2010) that are important for honey production in WA. Important forage species for honey production, such as karri (*Eucalyptus diversicolor*) and jarrah (*E. marginata*) are affected by soil-borne *Phytophthora* dieback (Benecke 2007). Furthermore, bushfire and prescribed burning also impact ecosystems within the southwest region (Bradshaw et al., 2018). Key bee forage species' response to fire during the juvenile period (defined as 'the time taken for at least 50% of individuals in a population to reach flowering age after fire' in (Bradshaw et al., 2018)) varies and depends on the frequency and intensity of burning (Bradshaw et al., 2018; Shedley et al., 2018), which may reduce reliability of sites for honey production.

The WA beekeeping industry is growing and facing a multitude of challenges affecting the long-term viability of the industry. Applying an SES approach can provide an improved understanding of the structural framing of beekeeping system in WA. Furthermore, the intrastate migrations presented by the specific spatial boundary makes the WA beekeeping industry a unique case for the first application of the social-ecological systems framework (SESF) to the beekeeping systems. Furthermore, a change in resource base (i.e., forage availability) for migratory beekeeping affects the spatial patterns of beehive migration and associated outcomes (Castellanos-Potenciano et al., 2017; Delgado et al., 2012; Pilati & Fontana, 2018), and an examination of these changes holds the potential to inform integrated resource management initiatives.

1.6 Research objectives and questions

The aim of this research is to develop a novel integrated modelling application describing the complex interconnectivities of the beekeeping social-ecological system to examine the impacts of existing and anticipated pressures on the industries sustainability. The following four research objectives and associated research questions provide the organisational structure for this body of work.

Objective 1: Identify the interconnections between bees - a critical group of insects with diverse economic, social, cultural, and ecological values - and people, through the lens of the Sustainable Development Goals (SDGs).

Research Questions:

(i) What are the interconnections between bees and people?

(ii) How can these interconnections help to achieve sustainable development?

Objective 2: Develop an understanding of the WA bee industry as a socio-ecological system through characterizing patterns, processes and feedback among system elements; and identify pressures currently acting on the bee-human system and their potential impact on the sustainability of the industry.

Research Questions

(iii) What are the social and ecological components of the WA commercial beekeeping system?

(iv) How do these components interact across space and time?

(v) What pressures are influencing the sustainability of the commercial bee-human system in WA?

Objective 3: Identify the change in the current geographic distribution of key bee forage species in Western Australia relative to future (~30 year) climate projections.

Research Questions:

(vi) What are the key bee forage species targeted by beekeepers in WA?

(vii) What is the spatial distribution of key bee forage species change under future projected climates?

Objective 4: Develop an agent-based model representing the beehive migration processes of commercial beekeepers in WA and examine how climate-induced changes in forage-availability will affect hive migration patterns.

Research Questions:

(viii) What are the current spatial patterns of beehive migration?

(ix) How does the current spatial patterns of beehive migration in the future based on changes in forage-availability?

(x) What are the spatial distribution of locations harvested by beekeepers now and in the future based on changes in forage-availability?

Describing the complex interconnectivities within an SES using integrated modelling is both a new and increasingly active area of research (Hamilton et al., 2015; Elsawah et al., 2020; Gain et al., 2020). In this research a novel application of integrating three well-established methods (i) stakeholder engagement (ii) species distribution modelling and (iii) agent-based modelling is presented to assess spatial patterns of beehive migration across the southwest of WA, and to describe how climate-induced changes in forage availability may influence patterns of future beekeeper mobility. The approach presented here builds upon the limited research focusing on modelling hive migration behaviour within a beekeeping SES to inform better environmental management decisions and ensure the future sustainability of the industry.

1.7 Thesis structure

This thesis is organised into seven chapters, including three papers and four supporting chapters. *Chapter 1: Introduction* provides the problem context of this research, set within the context of sustainability. *Chapter 2: Research methodology* includes an in-depth exploration of SES and related methodologies and presents a robust research design to guide the research presented in these pages. This research design draws upon both qualitative and quantitative methods which are presented in detail in *Chapters 3, 4, 5 and 6,* two of which represent peer reviewed publications.

Chapter 3 *Why bees are critical for achieving sustainable development* addresses the first research objective by highlighting the interconnections between bees and humans. As a peer-reviewed journal publication (published in *Ambio)*, the chapter illustrates the rationale for studying the bee-human system, outlining examples of bees' contribution to achieving 15 of the 17 SDGs as well as a range of SDG targets. The chapter concludes by suggesting eight thematic areas for further exploration of the complex interconnections within the bee-human system.

Chapter 4: Using a social-ecological system approach to enhance our understanding of structural interconnectivities within the beekeeping industry for sustainable decision making is a peer reviewed journal publication (published in *Ecology and Society*) addressing the second research objective. Here qualitative research methods including participant observation, semi-structured interviews and focus group dialogue, were used to characterize the WA commercial beekeeping industry as a socio-ecological system. The chapter presents the identification, verification and validation of 168 elements of the beekeeping SES as well as the interconnectivities among and between elements. Next, three priority pressures facing the sustainability of the state's beekeeping industry are identified including (i) availability, access and utilization of forage sites; (ii) burning of forage resources, and (iii) climate change. The chapter concludes by highlighting the importance of understanding SES complexities to improve the sustainable management of common pool resources to ensure effective pollination and sustained apiary production.

Building on the pressures identified in Chapter 4, *Chapter 5: Assessing impacts of climate change on the spatial distribution of key bee forage species in Western Australia*, highlights the geographic impacts of climate change on important bee forage species. The chapter addresses objective 3, specifically answering research question (vii) What is the spatial distribution of key bee forage species change under future projected climates? The chapter presents results identifying changes to the geographic distribution of honeybee forage which are then used to model changes in commercial hive migration patterns presented in the next chapter. Parts of this chapter have been published as a peer reviewed publication (published in *Data in Brief*) after the thesis examination was completed.

Chapter 6: B-Agent: A hybrid modelling approach for assessing the influence of variation in forage availability on spatial patterns of beehive migration presents the first agent-based model representing the beehive migration process (In revision with *Applied Geography*). The chapter outlines an original integrated modelling approach (*B-Agent*) used to address objective 4 of this research. The chapter focuses on the development of an ABM used to model the impacts of climate change (one of the priority pressures identified for the WA beekeeping SES) on key SES patterns (identified in Chapter 4). *B-Agent* draws on stakeholder engagement including semi-structured interviews, participatory mapping exercises, and machine-learning based species distribution modelling to examine forage-availability scenarios using an agent-based modelling approach. The chapter provides an evidence-based understanding of the propagation of impacts from a changing climate on the structurally interconnected beekeeping SES, resulting in variability in socioeconomic outcomes by reproducing the key social-ecological patterns of commercial beekeeping. Parts of Chapter 5 and Chapter 6 were prepared as a peer review publication (submitted to *MethodsX*) after the examination was completed.

Finally, *Chapter 7: General discussion and conclusions,* summarizes the findings and discusses implications for this research within the context of relevant scholarly studies. Specifically, the chapter discusses the contribution of this research to the field of social-ecological system modelling for sustainable natural resource management. The chapter concludes by outlining the limitations of the study and provides future pathways to advance the research presented in this document.

To summarise, using a case study of migratory beekeeping in Western Australia, this thesis presents a novel integrated modelling approach focusing on the key social-ecological interactions of commercial beehive migration. The research presents the first social-ecological system characterisation of the beekeeping system through the development of an integrated model, the *B-Agent*, focusing on modelling beehive migration patterns to better understand the effects of climate change and related pressures on the structurally interconnected beekeeping system. This thesis has been organised as a series of papers including three published papers (*Chapter 3*, *Chapter 4* and *Chapter 5*), one paper in revision (*Chapter 6*) and one paper in review (part of *Chapter 5* and *Chapter 6*). As such a certain degree of repetition is unavoidable as each results chapter represents a ‘standalone’ publication.

Chapter 2. Research Methodology

Beekeeping presents a unique system of interconnections between people and nature with a range of benefits to both ecological systems and society. A multitude of natural and anthropogenic pressures are impacting beekeeping interactions and associated benefits. Increasingly, researchers have initiated a discussion around the social-ecological relationship presented by the beekeeping system, but very little information is available to characterize beekeeping as a social-ecological system (SES). Migratory beekeeping presents spatially explicit interactions between the forage landscape, bees, and the beekeepers. Some approaches have attempted to capture these interactions to address the impacts of global change on beekeeping systems. However, beekeepers' decision-making, which is a major determinant of beehive mobility across the landscape, has received scant attention in migratory beekeeping models.

This presents two key research gaps including: (1) a systematic understanding and (2) lack of integrated for modelling migratory beekeeping within the context of a SES. The research presented in this thesis aims to address these two research gaps through four research objectives identified in Chapter 1. The research methodology employed in this thesis is founded on social-ecological systems (SES) thinking and an integrated modelling approach that combines multiple qualitative and quantitative techniques to address a limited understanding of beekeeping as an SES. By addressing each objective in turn, the basis to examine pressures acting on the system using an integrated modelling framework is established. Details on specific methods comprising the overall research design can be found in subsequent Chapters (Chapters 4, 5, and 6).

This chapter explains the theoretical framework and modelling techniques used in the research design process. First, the chapter provides a conceptual grounding of intertwined human-environment systems with a background of the SES concept and various SES frameworks. Second, the chapter highlights the approaches for modelling a SES with detailed explanation of the Agent-based modelling approach, which is used in this research. Finally, the chapter presents the overall research design used in this thesis for addressing the research gaps identified earlier in this section.

2.1 Social-ecological systems (SES)

The concept of social-ecological systems (SES) presents an integrated perspective of humans, nature, and their interactions (Berkes & Folke, 1998; Ostrom, 2009) – also termed coupled human-environment systems (Turner et al., 2003) or coupled human and natural systems (CHANS) (Liu et al., 2007). Explicitly thinking about the interconnections between humans and the environment in a systematic way is a relatively new concept. The term 'social-ecological systems' was first used in 1970, but since, the concept of intertwined human and natural systems has been further developed by Berkes and Folke (1998), with the SES concept evolving into various analytical frameworks widely used across different disciplines (Colding & Barthel, 2019; Folke et al., 2016).

Sustainable development underpins understanding and managing cross-scale interrelations and feedbacks among social, ecological and economic components of a system (Folke et al., 2002). The Sustainable Development Goals (SDGs) intertwine social, economic, and environmental targets as an "indivisible whole," but there is a lack of clarity about the interactions and interdependencies among SDGs, causing policymakers and planners to work in silos (Nilsson et al., 2016). The biosphere is the foundation for the SDGs (Folke et al., 2016; Leal Filho et al., 2018). SES operate within and depend upon the biosphere (Folke et al., 2016). Therefore, social-ecological interconnections can be made explicit among the SDGs to foster transformative change to progress towards sustainable development outcomes (Reyers & Selig, 2020; Selomane et al., 2019).

SESs are complex adaptive systems, in which system level properties emerge from an individual's behaviour or local level interactions among individuals (Levin et al., 2013; Preiser et al., 2018). The

SES is an open system that affects other systems and are affected by any number of influences (Biggs et al., 2021; Colding & Barthel, 2019). Therefore, understanding local level interactions and behaviour is critical to address these cross-scale influences. Significant progress has been observed in SES research over the last two decades (Colding & Barthel, 2019; de Vos et al., 2019). Most of this research is centred on pressing sustainability issues, through frequent use and development of new frameworks and place-based research (de Vos et al., 2019; Partelow, 2018).

2.2.1 Approaches for understanding SES

With the increasing recognition of the importance of understanding SES interconnectivities, a significant increase in SES research has been observed with a wide range of frameworks developed to study SESs (Colding & Barthel, 2019). However, three major analytical frameworks including the original SES framework (Berkes & Folke, 1998), the robustness framework (Anderies et al., 2004) and the multi-tier SES framework (Ostrom, 2009) have been widely used by SES researchers (Biggs et al., 2021; Colding & Barthel, 2019). The original SES framework developed by Berkes and Folke represents a descriptive approach, whereas the robustness framework developed by Anderies et al., and Ostrom's multi-tier framework are diagnostic frameworks that can be used to inform SES modelling (Colding & Barthel, 2019). Frameworks for examining socio-ecological systems differ significantly in how both the social and ecological portions of the systems are conceptualised, whether feedbacks are uni- or bi-directional and if the focus is analytical or practical (Binder et al.,2013). Ostrom's multi-tier framework treats ecological and social systems in equal depth, and explicitly addresses the reciprocity between both systems (Binder et al., 2013).

2.2.2 The Social-Ecological Systems Framework (SESF)

The SESF proposed by Elinor Ostrom and colleagues, represents the hierarchy of interacting variables under four core subsystems: resource system (RS); resource units (RU); governance system (GS); and actors (A). Each of these subsystems are nested in the broader social, ecological and political setting (S) and with feedback relationships to other ecosystems (E) (McGinnis &

Ostrom, 2014; Ostrom, 2009; Ostrom & Cox, 2010). These core concepts (subsystem) are termed as a "tier" in SESF. Each of these core concepts are first tier (i.e., the top level) concepts, which can be subdivided into a number of lower tiers, each of which can impact local data collection (Hinkel et al., 2015; Ostrom, 2009; Partelow & Winkler, 2016).

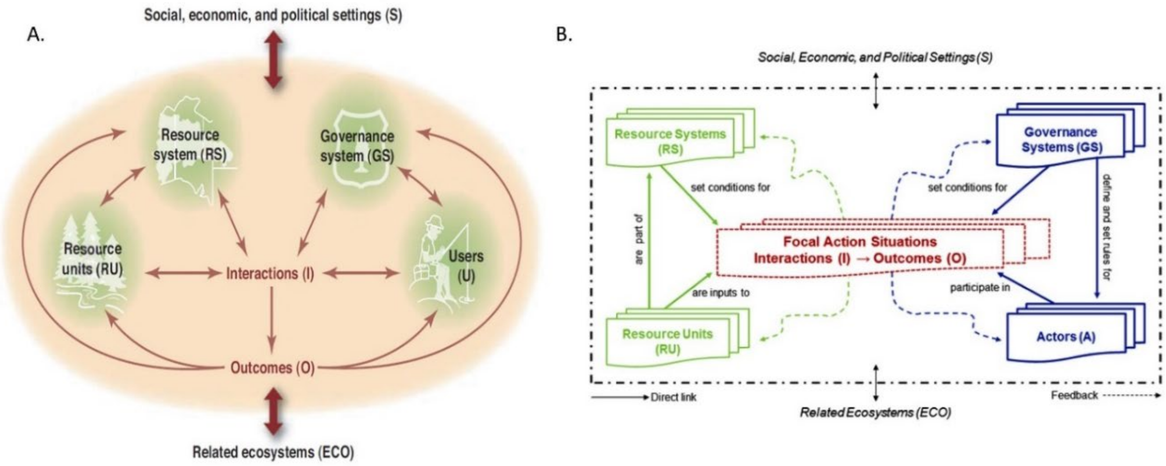

Figure 2: The Socio-ecological systems framework (SESF). A. General framework for analyzing SES sustainability (Ostrom, 2009); B. Revised SESF with multiple first-tier components (McGinnis & Ostrom, 2014).

SESF concepts were used interchangeably by various SES researchers leading to confusion, therefore, the SESF was generalized (see Figure 2) by replacing *Resource user* with *Actors* and including *Action situations* with *Interactions and Outcomes* (Ostrom & Cox, 2010). The term actors may represent individual or a group of individuals who extract resource units, build technical infrastructure or just obtain benefits from the resource (McGinnis & Ostrom, 2014). Action situations are the processes within an SES, which includes a set of actors, their positions, decisions and actions within the SES (McGinnis & Ostrom, 2014). SESF *Outcomes* emerge through the interactions between the *Actors* and the *Resource system* (McGinnis & Ostrom, 2014; Nassl & Loffler, 2015; Partelow & Winkler, 2016).

The application of the SESF spans a wide range of sectors including fisheries (Basurto et al., 2013; Cenek & Franklin, 2017; Ovitz & Johnson, 2019), aquaculture (Johnson et al., 2019; Partelow, Senff, et al., 2018), watershed management (Nagendra & Ostrom, 2014), coastal development, energy systems, and food systems (Marshall, 2015). Operationalising the SESF is complex particularly due to an often large number of nested variables (Frey, 2016; Hinkel et al., 2015; Leslie et al., 2015; McGinnis & Ostrom, 2014; Schlüter et al., 2014). The majority of SESF applications make use of both primary and secondary data. Since obtaining primary data to establish SESF variables is challenging and requires significant methodological attention, SESF is more frequently utilised as a conceptual tool than applied to empirical contexts (Partelow, 2018). Applying the SESF to a new industry in particular, is challenging because it requires designing a methodology for using the SESF from scratch (Partelow, 2018). Such sector-specific applications can significantly contribute to ongoing SESF development by strengthening methodological knowledge or providing guidance for the application of the SESF in various empirical contexts.

2.3 Modelling approaches for SES

A model is a simplified representation of a real-world system that can be used to understand and predict the behaviour of the system it represents (O'Sullivan & Perry, 2013). Modelling is a promising way to understand the specific role of each entity and the relationships within the system. Modelling SES is challenging, particularly due to methodological pluralism in the field (de Vos et al., 2019; Partelow, 2018). The challenges around SES modelling also lie in identifying important elements and relationships that must be modelled to operationalize the research question (Schlüter et al., 2014). SES are complex systems involving multiple entities connected with non-linear relationships that change over time (Levin et al., 2013). To understand complex, dynamic SES interactions, a variety of modelling approaches including system dynamics modelling, network analysis, agent-based modelling and integrated/hybrid modelling approaches are used (Gain et al., 2020; Martin & Schlüter, 2015). Agent-based modelling and network analysis are extensively used in SES research, particularly for capturing adaptive capabilities and emergent pattern within SES (Gain et al., 2020; Biggs et al., 2021). Moreover, SES modelling also needs to account for the mobility of elements within the system and incorporate human behaviour and decision-making (Lippe et al., 2019; Mallick, 2019). Integrating multiple data types and modelling approaches is a promising approach to capture complex, dynamic SES interactions (Hamilton et al., 2015).

2.4 Agent-based modelling (ABM)

Agent-based modelling (ABM) is a bottom-up modelling technique that helps understand complex systematic interactions among real-world entities and the emergent patterns resulting from these interactions (An et al., 2005; Grimm et al., 2005; Kelly et al., 2013; Lindkvist et al., 2020; Zvoleff & An, 2014). An ABM has three elements, (i) Agents, their attributes and behaviours; (ii) Agent environments; and (iii) the rules that govern interactions (Macal, 2018; Macal & North, 2010; Rounsevell et al., 2012). Agents can be any entity that is autonomous, self-contained and/or social (interacting with other entities), and performs actions or changes in state (Heppenstall et al., 2012; Macal, 2018; Macal & North, 2010). Agents can be related spatially or by means of a network, and often represent a clear link between model entities and their real-world counterparts (Lindkvist et al., 2020; Macal, 2018; Macal & North, 2010). Agent characteristics and relations are highlighted in figure 3.

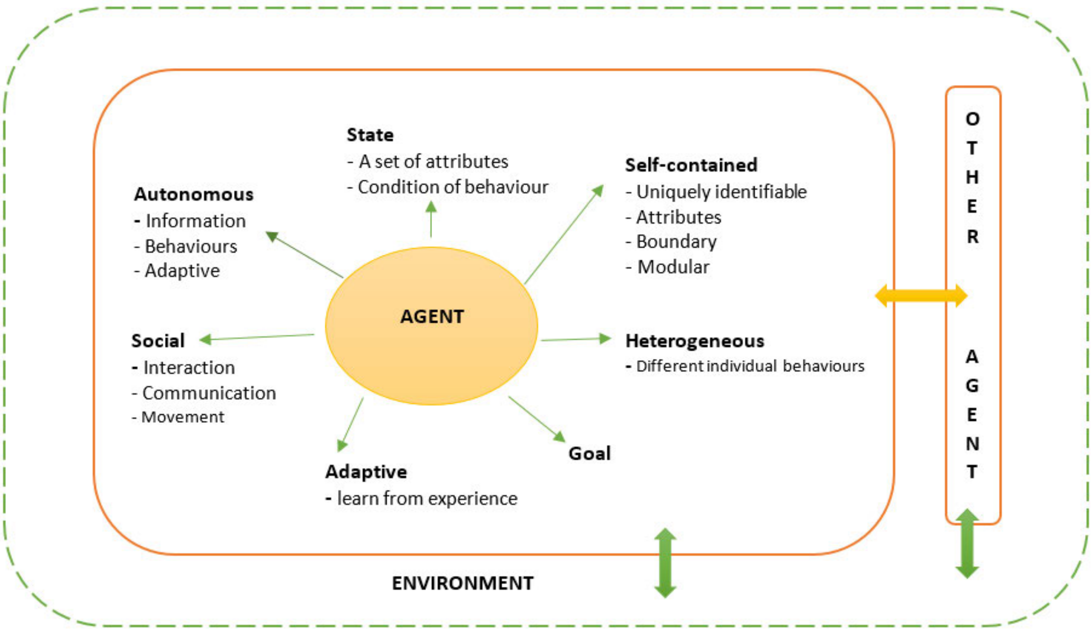

Figure 3: Agent characteristics, topology and environment (prepared based on (Macal, 2018; Murray-Rust et al., 2011; Rounsevell et al., 2012))

Agents in an ABM share common resources, can perceive changes in the environment, and are able to adapt their behaviour to these changes (Kelly et al., 2013; Lindkvist et al., 2020). ABM visualization is also very helpful for better understanding of complex interactions (Dorin & Geard, 2014).

In an SES, environmental change and migration are inextricably linked, where mobility patterns emerge from individuals' decision-making and interactions (Thober et al., 2018). ABM is widely used as a tool to model complex SES interactions (Filatova et al., 2013; Murray-Rust et al., 2014; Rounsevell et al., 2012; Gimblett, 2002). However, the popularity of ABM is due to its capability in modelling individual behaviours, understanding emergent properties at the system level, capturing the activities of mobile entities, and accounting for the human decision making process (Elsawah et al., 2015; Kelly et al., 2013; Schlüter et al., 2019; Zvoleff & An, 2014).

2.4.1 Approaches to create environments within ABM

Environments within an ABM are spaces where agents live and interact (Macal, 2018). ABM environments are spatial or network environments often with clear links to real-world environments where model agents are situated (Lindkvist et al., 2020). Some common approaches to create ABM environment are Cellular Automata (CA), Euclidian space, network model, Geographic information system (GIS) and non-spatial models such as Soup models where agents do not contain spatial information and perform random actions (Macal & North, 2010; O'Sullivan & Perry, 2013). Since the ABM environment defines the connections and interactions of agents, the creation of environments in ABM is always dependent on the research question at hand. Recent research has highlighted the utility of integrating other modelling approaches with an ABM to represent real-world dynamics within an ABM. For example, integration of system dynamics model with an ABM to understand social-ecological dynamics within lake restoration (Martin & Schlüter, 2015).

2.4.2 Species distribution modelling (SDM) for creating environment in ABM

An important aspect of a social-ecological systems is the environment in which it operates. The state of the forage environments plays a critical role in driving agent's actions. For example, availability of forage species across space and time, drives the behaviours of actors in an SES. Species distribution models provide an opportunity to integrate spatial and temporal dynamics of real-world environments in an ABM. Species availability in geographic space is related to the suitable environment and availability of biophysical resources required for a species to survive. Based on the statistical relationship between the location of species occurrences and environmental conditions, SDMs are widely used to study the current and future geographic distribution of both flora and fauna species (Elith et al., 2011; Resquin et al., 2020). Although estimating the state of coupled social-ecological climate conditions is a very complex endeavour, SDMs can provide important insights into likely future changes in resource distributions for use within integrated models and frameworks that inform the management of social-ecological systems under climate change (Miller & Morisette, 2014). Recent work by Holloway (2018) has used a similar integrated SDM-ABM approach to understand the dynamic relationship between biotic resources and oilbird (*Steatornis caripensis*) migration in Venezuela.

2.4.3 Incorporating decision-making in ABM

Agent's environment is one of the important factors that influence decision-making in ABMs. Across time, agents are exposed to new environments and decisions are made according to the state of the environment at a particular point in time. In the case of agents with low cognitive ability, decision making is unconscious (i.e., programmed in the organism's DNA) (DeAngelis & Diaz, 2019). Within an ant colony for example, when an ant finds food, it may directly return to the nest leaving a trail of pheromone that guide other ants to the food source (Detrain & Deneubourg, 2006). The complexity of representing conscious decision-making however, increases the cognitive ability of modelled agents to perform tasks.

Representing decision-making of humans in an ABM is an ongoing challenge, which has resulted in a large body of research attempting to implement various approaches and theories that represent human decisions in an ABM. Scholarly reviews of relevant literature can be organised into general decision making in ABMs (Balke & Gilbert, 2014; DeAngelis & Diaz, 2019), decision-making specific to ABMs representing migration (Klabunde & Willekens, 2016), human-decision making in social-ecological systems (An, 2012) and in land use ABMs (Groeneveld et al., 2017). Overall, these approaches highlight the state of agent environments, individual's knowledge of the environment and other agent actions affect agents' decision-making in an ABM. For example, in the case of an ABM used to model migration patterns, an individual might decide to migrate to a better environment if the benefits outweigh the cost (e.g., economic cost for human or energy consumption in animals) of migration. While the implementation of decision-making models in an ABM ranges from simple if-then statements to more complex algorithms (DeAngelis & Diaz, 2019) with bounded rationality the most commonly used behavioural paradigm (Groeneveld et al., 2017; Schwarz et al., 2020).

Bounded rationality represents the limited rational choices available to an individual at any point in time (Simon, 1990). Boundedly rational actors often use heuristic rules to optimize behavioural strategies (Ostrom, 1998). The heuristics rules refer to sets of rules that bounds agent's knowledge of available options (Todd & Gigerenzer, 2000). Satisficing heuristics are a set of aspirational criteria that an individual establishes, and when met, terminates their search for alternatives. In simple words, satisficing is a heuristic search with a stop rule (Schilirò, 2018; Todd & Gigerenzer, 2000). For example, in an ABM of behavioural change in pastoral systems by Dressler et al. (2019), a household's needs are characterised by a satisfying threshold of herd size and preference for pasture resting, the household agent will select the first pasture with sufficient biomass that matches its satisficing threshold. The SESF supports bounded rationality, in which actors make goal-oriented choices by using simple heuristics like satisficing (Biggs et al., 2021).

2.5 Research design

Significant progress has been made in theoretical and model-based understanding of SES, yet developing place-based and sector-specific understanding of SES and developing novel approaches/applications for modelling SES remains an active research area. To this end, a two-phase research design including (i) Phase 1 – System understanding, and (ii) Phase 2 – Integrated modelling is proposed in this thesis (presented in Figure 4). Each phase aimed at addressing two research objectives and a collection of research questions by using multiple methods for answering each.

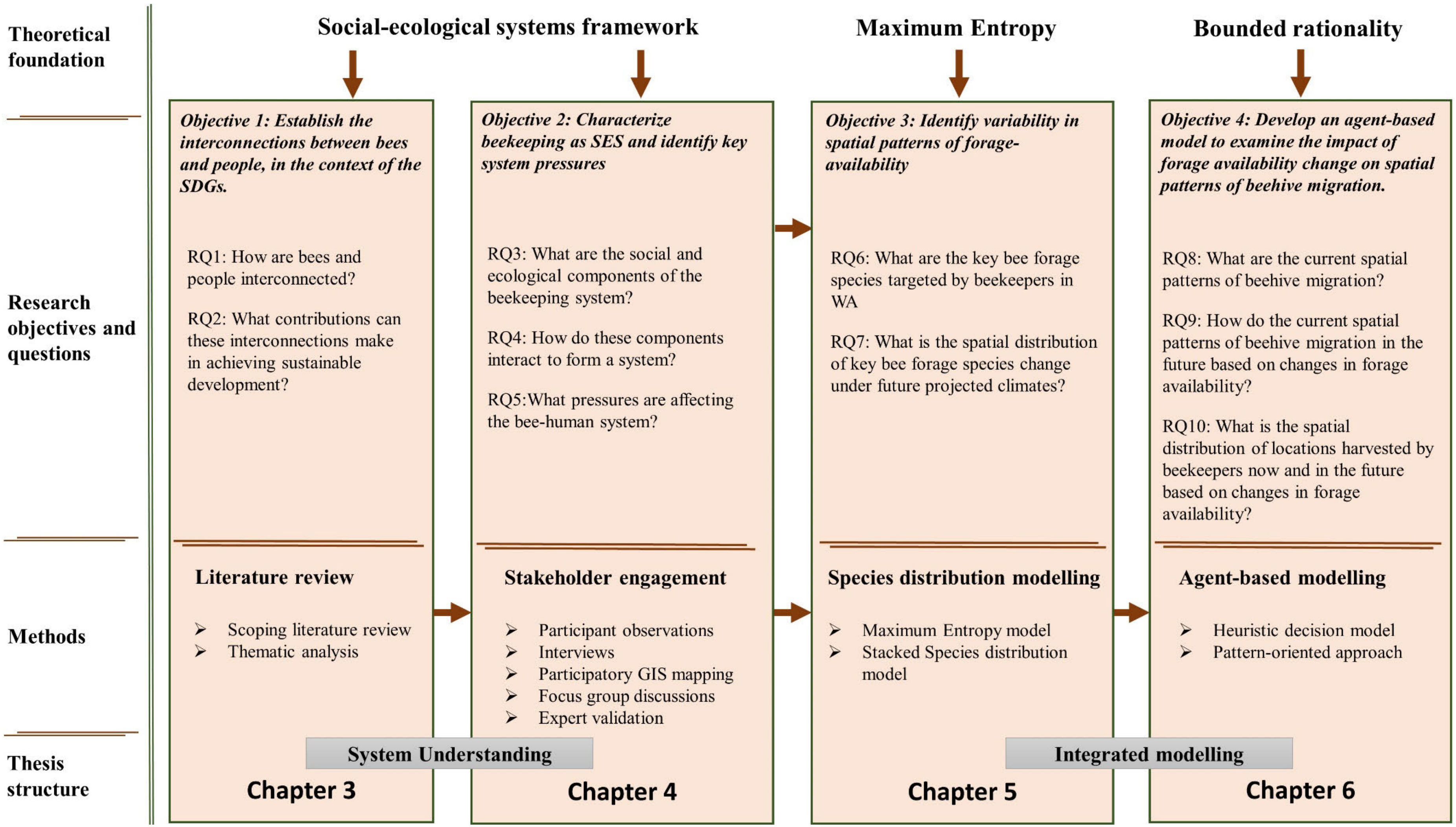

Figure 4: Overview of the theoretical framework and methodology used to address each research objective.

2.5.1 Beekeeping as an SES

The SES understanding of bee-human relationships lays the foundation for this research. To date, approaches examining the interdependent bee-human relationship have focused only on siloed dimensions of this relationship, primarily bee colony dynamics (e.g., Johannsen et al., 2021). Studying the bee-human system through an SES lens allows for the identification and management of system drivers, activities, and processes that contribute to the sustainable development of the system (Matias et al., 2017) through improved environmental management and governance (Rodela et al., 2019). Application of the SES approach to a study of bee-human systems is in its infancy (Malkamäki et al., 2016), with limited examples of the use of SES thinking to examine traditional honey gathering practices (Matias et al., 2019) and wild bee-human interactions (Matias et al., 2017). Despite growing discussions of the mutualistic relationship between bees and humans, there is still a significant gap in understanding the components, interconnections, and interactions within a bee-human system.

The system understanding phase aims to close this gap by improving conceptual understandings of the bee-human SES (Objectives 1 and 2). Specifically, the first objective was achieved through reviewing the literature illustrating bee-human interconnections to highlight the contribution of this relationship towards achieving sustainable development and identify key thematic areas for further exploration of these complex interconnections (Chapter 3). This step provided a strong foundation for achieving the second objective, which involved applying Elinor Ostrom's SES framework (SESF; McGinnis & Ostrom, 2014) to a commercial beekeeping system (i.e., RQ 3, 4 and 5 demonstrated in Chapter 4 as multi-tier SES variables, key interactions and important pressures impacting the beekeeping SES).

The application of the SESF to the beekeeping system was guided by the diagnostic procedures discussed in Hinkel et al. (2015). The Beekeeping SESF was conceived and validated through iterative stakeholder engagement using a variety of methods. To start, a foundational understanding of the beekeeping SES including actors, and their complementary and contrasting views about the beekeeping system was obtained through participant observation methods (e.g., attending formal meetings and informal gatherings of beekeeping organisations). Based on this understanding, semi-structured interviews (see Appendix 4 for interview themes) were conducted with two stakeholder groups including commercial beekeepers (> 50 hives), and government officials, to prepare a list of SESF variables, which were then verified and validated through an independent advisory group and an expert panel of retired beekeepers. Information on the spatial-temporal availability of target forage resources was then collected through participatory Geographic Information Systems (GIS) mapping with individual beekeepers.

Further details concerning how the beekeeping SESF was developed, and the various stakeholder engagement methods used to do so, are included in Chapter 4. During this phase, key social-ecological interconnectivities and pressures impacting the structurally interconnected beekeeping SES were identified. Developing evidence that combines biophysical and socio-economic data demonstrate such intertwinedness between social and ecological systems and is critical for informing sustainable management decisions (Guerry et al., 2015; Virapongse et al., 2016). Towards this, the next phase was initiated, aiming to develop a quantitative evidence base to support sustainable decision-making within the beekeeping SES.

2.5.2 Integrated modelling

Although the importance of forage landscapes in apiary site selection decisions (Galbraith et al., 2017; Pantoja et al., 2017; Zoccali et al., 2017) and the overall sustainability of migratory beekeeping (Pilati & Prestamburgo, 2016) is increasingly emphasized in the literature, the interdependence of the forage landscape and beekeeper migratory behaviour is often overlooked in beekeeping models. The integrated modelling phase of this research focuses on developing a quantitative evidence base explaining this interconnectivity within the beekeeping SES. Here, an integrated spatial model *B-Agent,* was developed addressing Objectives 3 and 4 to explain how changes in forage landscapes are reflected in beehive migration patterns. *B-Agent* draws upon two separate modelling approaches including a species distribution model (Chapter 5) and an agent-based model (Chapter6), which use data collected through stakeholder engagement (i.e., target forage species, their spatial locations, and key factors that affect beekeepers' decision-making for apiary site selection), and previously published/unpublished spatial and aspatial data (i.e., flowering occurrences of target forage species, bioclimatic information, hive holding (ownership) ranges and the residential addresses of beekeepers). An overview of each modelling approach is provided in the following sections with specific details included in Chapters 5 and 6.

Based on the results of the stakeholder engagement (i.e., semi-structured interviews (Chapter 4) and participatory mapping phases (Chapter 6)), SDMs of key bee forage species were used to build a representation of beekeeping forage-availability across space and time. The presence-only Maxent SDM was used to estimate the probability of species occurrence in current climate conditions, and the likely change of each in 2055 (reported in Chapter 5). The SDMs for individual forage species were then stacked (S-SDM) based on the month of flowering to provide for the changing geographic distribution of target bee forage and its richness (included in Chapter 6). The S-SDMs generated in this step were integrated as input forage availability environments in an agent-based beehive migration model explained below (presented in Chapter 6).

Bounded rationality, particularly satisficing heuristics, forms the theoretical foundation for incorporating beekeepers' decision making in a hive migration ABM. The satisficing heuristics is particularly used for sequential searching where agents search for certain aspirational criteria and terminate the search when the location satisfies the agent is found. Beekeepers' higher preference for accessing a forage site with variety of nectar and pollen resources has been highlighted in recent studies (Camargo et al., 2014; Galbraith et al., 2017; Zoccali et al., 2017). Therefore, a combination of maximizing and satisficing heuristics is used to derive decision-making rules for beekeeper agents. For example, beekeeper agents first try to maximize their return on investment (e.g., search for sites with highly preferred forage resources), but when unable to meet the maximizing option, select an option that at least satisfies a set of predetermined criteria (e.g., any available forage). The selection of heuristic decision modelling based on empirical data was primarily due to inadequate data to calculate preference or utility functions which are commonly used to model human mobility in ABMs. If-then rules implemented in hive migration ABM (presented in Chapter 6) for selecting forage sites were developed based on stakeholder engagement (Chapter 4).

2.6 Conclusion

The research design employed in this thesis, encompasses two phases: system understanding and model integration. System understanding began with gathering knowledge about socio-ecological concepts from system stakeholders and available literary sources, followed by iterative stakeholder engagement to conceptualise a commercial beekeeping SES, identify interconnectivities, and system pressures. Based on the knowledge acquired during the system understanding phase, the integration phase then identified the key SES interconnectivities required to model (e.g., forage landscape and beehive migration), and select the modelling approaches that can best represent the dynamics of each social and ecological entity that partakes in interconnectivities being modelled. Finally, integrate the selected modelling approaches to estimate the impacts of SES pressures. For example, in this thesis, the SDM was chosen to incorporate the dynamics of forage-availability environments within an ABM of hive migration decision making. Although, the integrated modelling approach (*B-Agent*) presented in this thesis highlights a case study application focusing on the impacts of climate change on the beekeeping SES in WA, the design focus of the approach (i.e., integrating forage landscape and beekeeping decisions) makes it useful for assessing the impacts of other pressures (e.g., land use change). Moreover, while the methods were developed to answer specific research questions for the WA migratory beekeeping SES, general research steps can be used to guide integrated model development for addressing sustainability pressures on other similar SESs.

Chapter 3. Why bees are critical for achieving sustainable development

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Abstract:

Reductions in global bee populations are threatening the pollination benefits to both the planet and people. While the contribution of bee pollination in promoting sustainable development goals through food security and biodiversity is widely acknowledged, a range of other benefits provided by bees has yet to be fully recognised. We explore the contributions of bees towards achieving the United Nation's Sustainable Development Goals (SDGs). Our insights suggest that bees potentially contribute towards 15 of the 17 SDGs and a minimum of 30 SDG targets. We identify common themes in which bees play an essential role, and suggest that improved understanding of bee contributions to sustainable development is crucial for ensuring viable bee systems.

3.1 Introduction

The United Nations' 17 Sustainable Development Goals (SDGs) are designed to achieve synergy between human well-being and the maintenance of environmental resources by 2030, through the pursuit of 169 targets and more than 200 indicators (UN, 2015). The biosphere is the foundation for all SDGs (Folke et al., 2016; Leal Filho et al., 2018; Rockström & Sukhdev, 2016), and yet biodiversity conservation remains a persistent global challenge (Tittensor et al., 2014). An examination of how a particular suite of organisms within the global wealth of biodiversity can contribute to the attainment of the SDGs holds the potential to link sustainable development policy with conservation through the design of integrated solutions. We explore the interconnections between bees - a critical group of insects with diverse economic, social, cultural and ecological values - and people, in the context of the SDGs.

3.1.1 Bees, people and the planet

Bees comprise ~20,000 described species across seven recognised families (Ascher and Pickering 2014), with many more species yet to be described (Figure 5). The evolutionary radiation of bees coincided with the evolutionary radiation of flowering plants (Cappellari et al., 2013), and they occupy an important ecological role as pollinators of a range of flowering plant species. Although bees are not the most diverse group of pollinators (the butterflies and moths comprise over 140,000 species), they are the most dominant taxonomic group amongst pollinators; only in the Arctic regions are another group (flies) more dominant (Ollerton, 2017). Bees' ability to transport large numbers of pollen grains on their hairy bodies, reliance on floral resources, and the semi-social or eu-social[1] nature of some species are among the characteristics that make them important and effective pollinators (Klein et al., 2018; Ollerton, 2017). Fifty bee species are managed by people, of which around 12 are managed for crop pollination (Potts et al., 2016a).

The potential importance of bees for crop pollination has been highlighted as a particular reason to conserve wild bees and their habitat (Gill et al., 2016; Klein et al., 2007; Klein et al., 2018; Potts et al., 2016b). More than 90% of the world's top 107 crops are visited by bees, however, wind- and self-pollinated grasses account for around 60% of global food production and do not require animal pollination (Klein et al., 2007). Wild bees contribute an average of USD$3,251 ha^{-1} to the production of insect-pollinated crops, similar to that provided by managed honeybees (Kleijn et al., 2015). A very small number of mostly common wild bee species provide the majority of bee-related crop pollination services (Kleijn et al. 2015), and other insects such as flies, wasps, beetles, and butterflies have an important, underemphasised role in crop pollination (Rader et al., 2016).

[1] Eu-social nature of species refers to species living in a group of multiple generations of conspecific adults. Such groups show cooperative behaviour for brood care and non-reproductive workers {Anderson, 1984 #1220}.

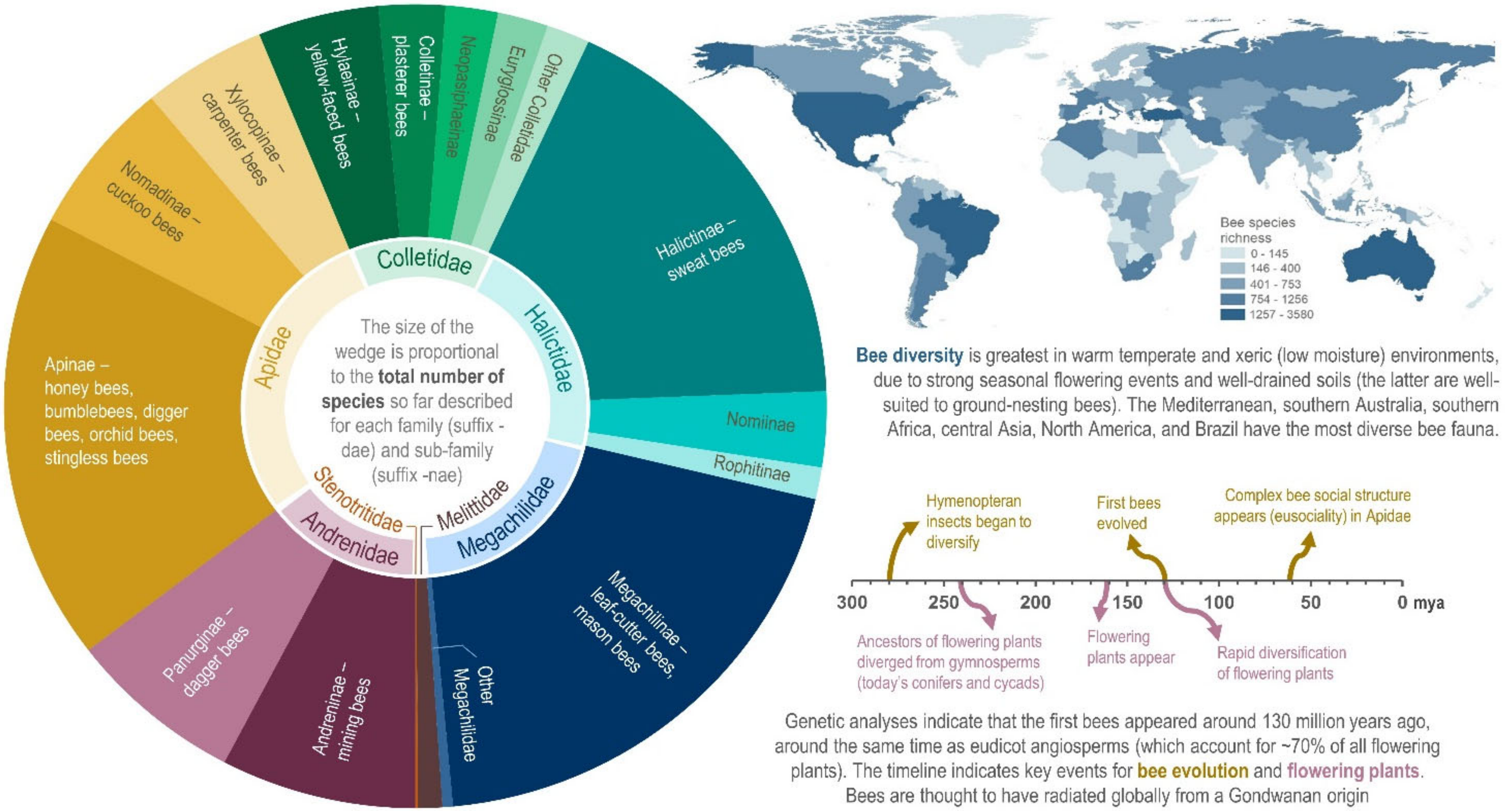

Figure 5: A snapshot of the diversity of bees. Bees are taxonomically classified under the insect Order Hymenoptera, along with ants, wasps and sawflies, and are part of the superfamily Apoidea, and clade Anthophila, with seven recognised families. Although only 50 of the ~20,000 described bee species are actively managed by people, the entire clade is important for ecosystem functioning and human well-being. Bees and flowering plants have co-evolved, making bees effective pollinators of a large proportion of flowering plant species. There are perhaps a further ~5,000 bee species that are yet to be described. Data source: Ascher and Pickering (2014). Information for this figure was sourced from Michener 1979; Michener 2000; Michez and Patiny 2007; Litman et al. 2011; Cappellari et al. 2013; Peters et al. 2017; Meiners et al. 2019.

Such research has highlighted the danger of exclusively highlighting the importance of bees for crop pollination, to the potential detriment of conserving diversity across the landscape (Kleijn et al., 2015; Senapathi et al., 2015). In our assessment of bees and the SDGs, we highlight that the diversity of wild and managed bees have crucial ecological, economic and social importance including and beyond crop pollination.

Long-standing associations exist across multiple bee species and human societies. Documented ancient bee-people interactions include honey hunting dating back to the Stone Age for the honey bee *Apis mellifera* in Europe (Roffet-Salque et al., 2015), more than 2000 years of keeping the honey bee *Apis cerana* in Asia (Crane, 1995), and beekeeping reaching back to at least pre-Columbian times for stingless bees (*Melipona beechii*) in Mayan Mexico (Quezada-Euán, 2018). Bees also appear in many religious scriptures and are found within mythology, cosmology and iconography (Fijn, 2014; Roffet-Salque et al. 2015; Potts et al., 2016a; Quezada-Euán, 2018). Beeswax from culturally significant sugarbag bees (*Tetragonula* spp.) has been used in the production of rock art by Aboriginal peoples in northern Australia for at least 4,000 years (Watchman & Jones, 2002). In Greek society, bees are closely linked with the cycle of birth and death, and considered an emblem of immortality (Cook, 2013). “Telling the bees” was a popular tradition in 19th C New England; it was customary for keepers to inform their bees of any major event such as a birth, death, marriage or long journey (Hagge, 1957).

Today, the long-standing mutualistic relationship between bees and people is jeopardised by recent reported declines in bee populations (Potts et al., 2016b). The loss of managed honey bee colonies (e.g., Potts et al. (2010a)) and declines in wild bee pollinators (e.g., Biesmeijer et al. (2006); Koh et al. (2016)) have been observed, particularly in Europe and North America. However, much remains undocumented about the conservation status of most bee species (Goulson et al., 2015; Jamieson et al., 2019). The global conservation status of just 483 bee species has been assessed by the IUCN, most of which were ‘data deficient’ (IUCN 2019). The European Red List assessment of 1,965 species of European bees found that 9.2% were threatened (Nieto et al., 2014). Goulson et al. (2015) reason that declines in wild bees definitively noted for Europe and North America are likely to have occurred elsewhere.

With a decline in bee populations there has been a surge of research focusing on the drivers of bee decline and the impacts on provisioning ecosystem services (Decourtye et al., 2019; Goulson et al., 2015). Drivers such as habitat loss, pesticide use, the proliferation of parasites, availability and diversity of forage, change in land use and climate, and species competition have all contributed to the reduction in bee populations (Goulson et al., 2015; Sánchez-Bayo & Wyckhuys, 2019). These drivers interact in complex ways; for example, market-driven agricultural intensification has limited bees’ access to forage resources while potentially increasing bees’ exposure to harmful agrichemicals (Durant, 2019). People can act as a positive influence for ecosystem function through designing bee-friendly policies and contributing to bee conservation approaches (Hill et al., 2019; Matias et al., 2017; Potts et al., 2016a). Acknowledging the plethora of literature addressing the decline in bee populations and the consequences for agriculture, we contend that the ubiquitous importance of bees in connecting the biosphere (which we use interchangeably with the term ‘planet’) and people remains relatively less explored, particularly with regard to broader goals in sustainable development.

3.2 Framing the broader importance of bees to sustainable development

Bees provide a range of ecosystem services that contribute to the wellbeing of people while maintaining the planet’s life support systems (Gill et al., 2016; Matias et al., 2017). Ecosystem services inherently contribute to achieving global sustainable development (Wood et al., 2018). Yet the extent to which bees contribute towards the achievement of the full suite of the SDGs has not been explored in detail. Existing research has highlighted the importance of insects in achieving multiple SDGs through the regulation of natural cycles, biological pest control, pollination, seed dispersal, and even as bio-inspiration (Dangles & Casas, 2019; Gill et al., 2016; Sánchez-Bayo & Wyckhuys, 2019). Bee pollination has been identified as directly contributing to food security (SDG2) and biodiversity (SDG15) (Dangles & Casas, 2019). However, bees could also contribute to a broader range of SDGs.

We explicitly identify the realised and potential contributions of bees towards achieving the SDGs, presenting evidence to highlight the interconnectedness between bees, people and the planet from an integrated systems perspective (Stafford-Smith et al., 2017). We review the SDGs alongside the potential contributions of bees in achieving individual SDG targets. As the SDGs explicitly build on the foundation of the biosphere (Folke et al. 2016, Leal Filho et al. 2018), the perspective presented here may help in designing implementation pathways to achieve SDG targets. We identify 30 targets to which bees may contribute (Table 1) through a range of direct and indirect connections between bees, people and the planet.

We incorporate contributions from all bee species, including wild and managed populations. The European honey bee (*A. mellifera*) and buff-tailed bumblebee (*Bombus terrestris*) could be considered as 'massively introduced species' having greatly expanded their geographic range through human management and escape (Geslin et al., 2017). We note the extensive and evolving literature on the interactions between native wild bees, introduced domesticated bees, and feral bees, noting evidence of competition for forage and nesting resources, disruption of native plant-pollinator networks, and potential for viral disease transmission between species (e.g., Geslin et al. (2017); Mallinger et al. (2017); Alger et al. (2019); Wojcik et al. (2018); Murray et al. (2019); Valido et al. (2019)). We pursue a holistic perspective that encompasses native wild and managed introduced bees, following Kleijn et al.'s (2015; 2018) calls for an inclusive approach that safeguards all pollinators.

Table 1: The contributions of bees towards relevant SDG targets

SDG	Goal	Contributions from bees to SDG targets	Details on the contributions bees provide towards achieving the SDG targets
1	No Poverty	1.1, 1.4, 1.5	Keeping bees offers economic diversity as an income source (1.1), helping build resilient livelihoods for poor and vulnerable peoples (1.5), whilst provides equal access to economic and natural resources for both men and women (1.4).
2	Zero hunger	2.2, 2.3	Bee pollination increases crop yield (2.3) and enhances the nutritional value of fruits, vegetables and seeds (2.2).
3	Good health and well-being	3.3, 3.8, 3.9	Bee products provide safe and affordable medicinal sources (3.8) used in traditional and modern medicine to treat chronic diseases such as cancer through strong bioactive compounds (3.3). Bee pollination contributes to the growth and diversity of plants that are important for improved air-quality and nutritious food (3.9).
4	Quality education	4.3, 4.4, 4.5	Vocational training for keeping bees can enhance equal opportunities for employment, training and entrepreneurship among men, women and indigenous people (with traditional knowledge) (4.3, 4.4, 4.5).
5	Gender equality	5.5, 5.a	Keeping bees as a hobby or being involved in beekeeping can enhance opportunities for women's involvement in economic, social and political decision making processes even in communities that deprive women of property rights (5.5, 5.a).
6	Clean water and sanitation	6.6	Bee pollination contributes to growth and diversity in water-related ecosystems enhancing filtration rates; revegetation offers enhanced purification opportunities and new resources for commercial bee operations (6.6).
7	Affordable and clean energy	7.2	Bee pollination improves production for biofuel/oilseed crops such as Sunflower, Canola, and Rapeseed (7.2).
8	Decent work and economic growth	8.1, 8.6, 8.9	Improved agricultural production from bee pollination contributes to gross domestic products (8.1). Beekeeping can diversify livelihood opportunities for men and women in rural areas (8.6) and support nature-based tourism initiatives (8.9).
9	Industry innovation and infrastructure	9.b	Bees are an element of nature that inspire human innovations e.g., airplane design and computer algorithm development; and new honey related products (9.b).
10	Reduced inequality	10.1, 10.2	Improved livelihoods from beekeeping and the contribution of bee pollination towards GDP can support sustainable income growth for lower income groups (10.1) and promote inclusive social, economic and institutional development (10.2).

SDG	Goal	Contributions from bees to SDG targets	Details on the contributions bees provide towards achieving the SDG targets
11	Sustainable cities and communities	11.6, 11.a	Bee pollination of urban flora supports improved local air quality (11.6), enhances aesthetic values of urban gardens, public open spaces and improves backyard food production (11.a).
12	Responsible consumption and production	12.3, 12.b	Bee pollination can contribute to reducing food waste by improving visual aesthetics of food (shape, size and colour) and increase shelf life (12.3). Beekeeping can be marketed as sustainable tourism for regional development (12.b).
13	Climate actions	13.3	Use of bees and bee products for environmental monitoring can improve understanding of climate impacts on the environment (13.3).
14	Life below water	14.4	Bees contribute to improved production of plant-based nutrient alternatives to fish (nuts and seeds). Overharvesting of fish can be managed by promoting production and consumption of alternative plant based nutrient sources (14.4).
15	Life on land	15.1, 15.5, 15.9	Bees contribute to biodiversity by pollinating flowering trees and plants (15.5) and contributing to forest conservation (15.1). Incorporating beekeeping in local planning processes may support reforestation activities which may result in poverty reduction and sustainable regional development (15.9).

*[*]SDG16 (peace, justice and strong institutions) and SDG17 (partnership for the goals) were excluded from this analysis given their focus on governance and policy. **Supporting literature includes a mix of direct and indirect evidence. The details on bees' potential contribution to SDGs have been provided using the language used in SDG targets, which may differ from the language used in the supporting literature.*

3.2.1 The identified critical role of bees in sustainable development

The importance of bee pollination for food crops has been widely acknowledged, with growing concern of a global crisis as demand for pollination services continues to outstrip supply, with an associated increase in less diverse, pollinator-dependant agriculture systems (Aizen & Harder, 2009). In addition to improving the yield of some crops (target 2.3) Klein et al. (2007), 2018; Stein et al. (2017)), bee pollination contributes to enhanced nutritional value (target 2.2) and improved quality and longer shelf life of many fruits and vegetables (Klatt et al., 2014), which could potentially help in reducing food waste (target 12.3) resulting from aesthetic imperfections (Gunders & Bloom, 2017).

Less explored aspects of bee pollination include the contribution to biofuels (SDG7). Despite being self-pollinated, oil seed crops show increased yield when pollinated by bees (target 7.2) (Halinski et al., 2018; Perrot et al., 2018). Research in Mexico on the performance of bees on *Jatropha curcas* found significant improvement in the seed set when the self-pollinated varieties were supported with bee pollination (Romero & Quezada-Euán, 2013). Canola, another self-pollinating oilseed crop, also shows a positive association between higher yields and bee diversity (Halinski et al., 2018; Manning & Boland, 2000).

Beyond agricultural landscapes, research in urban bee ecology aids understanding of bee dynamics in our cities and informs urban bee conservation initiatives (Hernandez et al., 2009). Urban beekeeping strengthens residents' connection to nature (Stange et al., 2018). Planting aesthetically pleasing, bee-attractive flowering species in landscape planning can provide forage for bees, and close proximity to such plantings may result in pollination rewards for trees and other species in public green spaces (target 11.7) (Hausmann et al., 2016; Lowenstein et al., 2015). European honey bees can be used as an indicator species for tracking contaminants and monitoring environmental health (target 13.3) in urban areas (Zhou et al., 2018). In addition, understanding bee forage preference, suitability of habitat and mobility between different habitat types is critical for designing sustainable urban (target 11.7) and rural landscapes (target 15.9) to optimize pollination benefits as well as support bee health (Langellotto et al., 2018). For example, the United Kingdom's Protection of Pollinators Bill was proposed to develop a national network of wildflower corridors called B-lines to support bee populations and other pollinators (UK Parliament, House of Commons, 2017).

The contribution of wild and managed bees in pollinating wild plants in natural ecosystems and managed forests (target 15.1) is well-acknowledged (Klein et al., 2018; Senapathi et al., 2015). The biodiversity found within forests provides a critical range of ecosystem services including water cycle regulation (target 6.6) and carbon sequestration (Brockerhoff et al. 2017; Creed and van Noordwijk 2018). Bee–pollinated plants provide a source of food for wildlife and non-timber forest products for people (Bradbear, 2009; Senapathi et al., 2015). For example, Brazil nut trees (*Bertholletia excelsa*) require bee pollination to set their high-value fruit, with much greater productivity in the wild, likely due to low numbers of native bees in plantations (Cavalcante et al., 2012). Beekeeping within forest boundaries can support forest conservation (target 15.1) alongside rural livelihoods (Chanthayod et al., 2017; Mudzengi et al., 2019; Sande et al., 2009).

Keeping bees provides opportunities for income diversity (target 1.1) with low start-up costs and diverse products including honey, pollen, beeswax, propolis, and royal jelly, or through pollination services (Bradbear, 2009). Initiatives to promote beekeeping and pollination services in Kenya have resulted in livelihood improvements for smallholder farmers through increased farm productivity and an additional income stream (target 1.5) (Carroll & Kinsella, 2013). However, in other regions of Africa, constraints to improve livelihoods through bee-related activities have been attributed to a lack of knowledge concerning bee husbandry processes, access to equipment, and training (Minja & Nkumilwa, 2016). Vocational education in beekeeping (target 4.3) could promote economic opportunities for employment and entrepreneurial enterprise (targets 8.6 and 4.4) and diversification for Indigenous groups (targets1.4 and 4.5), as well as help empower women (target 5.5) including those within traditionally patriarchal societies to promote gender equality (target 5.a) (Mburu et al., 2017; Pocol & McDonough, 2015).

Beekeeping can be an important strategy for livelihood diversification (Bradbear, 2009), which can directly contribute to an increase in per capita and household income (target 8.1) (Chanthayod et al., 2017; Mazorodze, 2015) and also allow for enhanced fiscal opportunities (e.g., tourism) and sustained income growth for people in rural areas, irrespective of social and economic status (targets10.1 and 10.2) (Pocol & McDonough, 2015; Vinci et al., 2018). An initiative for sustainable tourism in Slovenia, packages bee-related education and healing experiences with bee products, together with opportunities to create and purchase original crafts using bee products (Arih & Korošec, 2015). In Fiji, The Earth Care Agency is working to promote organic honey production on remote islands to provide economic alternatives for indigenous Fijians (Matava Fiji Untouched, 2019). These initiatives contribute to local economies and in the case of Slovenia, help in marketing the country's natural attractions whilst providing additional livelihood opportunities through increased tourism activities (target 8.9).

In relation to health, honey, bee pollen, propolis, royal jelly, beeswax and bee venom have all been used in traditional and modern medicine (target 3.8) (Easton-Calabria et al., 2019; Kocot et al., 2018). Researchers have identified bioactive properties of honey, propolis and royal jelly which suggest the presence of compounds with antimicrobial, anti-inflammatory, antioxidant, antitumor, and anticancer activities (Easton-Calabria et al., 2019; Pasupuleti et al., 2017). Honey is used in wound and ulcer care, to enhance oral health, fight gastric disorders, and liver and pancreatic diseases, as well as promote cardiovascular health (Pasupuleti et al., 2017). Propolis is used in gynaecological care, oral health, dermatology care, and oncology treatments, whilst royal jelly is used in reproductive care, neurodegenerative and aging diseases, and wound healing (target 3.4) (Pasupuleti et al., 2017).

Bees have contributed to industry, innovation and infrastructure by inspiring the design and development of a range of structures, devices and algorithms that can benefit sustainable development (target 9b). The honeycomb structure of beehives is often a mainstay in structural engineering (Zhang et al., 2015). Drawing inspiration from bee anatomy, the medical industry has benefited from innovations such as surgical needles adopted from the design of bee stingers (Sahlabadi & Hutapea, 2018). Bee behaviour has inspired complex computer-based search and optimisation processes informing a new wave of genetic algorithms (Xing & Gao, 2014).

3.3 Towards sustainable bee systems

The decline in global insect populations has attracted the attention of the scientific community, general public and policymakers (Potts et al., 2016b), with heightened public awareness of the importance of bees for pollination. Our research has highlighted the contribution bees can provide towards achieving a diverse range of SDG targets in addition to their crucial role in pollination. The increasingly positive attitude of the public towards bees and insect pollinators more broadly provides opportunities for efforts to conserve bee habitat and support pro-pollinator initiatives in land management, agricultural diversification and urban greening (Schönfelder & Bogner, 2017).

A holistic view of ecosystems including wild and managed bees and humans is necessary to address sustainability challenges (Klein et al., 2018; Saunders et al., 2018). By employing a systems approach, we can better understand the interconnections between elements within coupled human-environment systems. We strongly advocate the need for appropriate natural resource management approaches for maintaining a balanced system as vital for allowing bees continued success in their natural role. We summarise our findings by suggesting eight key thematic priority areas whereby bees can play a crucial role in meeting the SDGs (Figure 6).

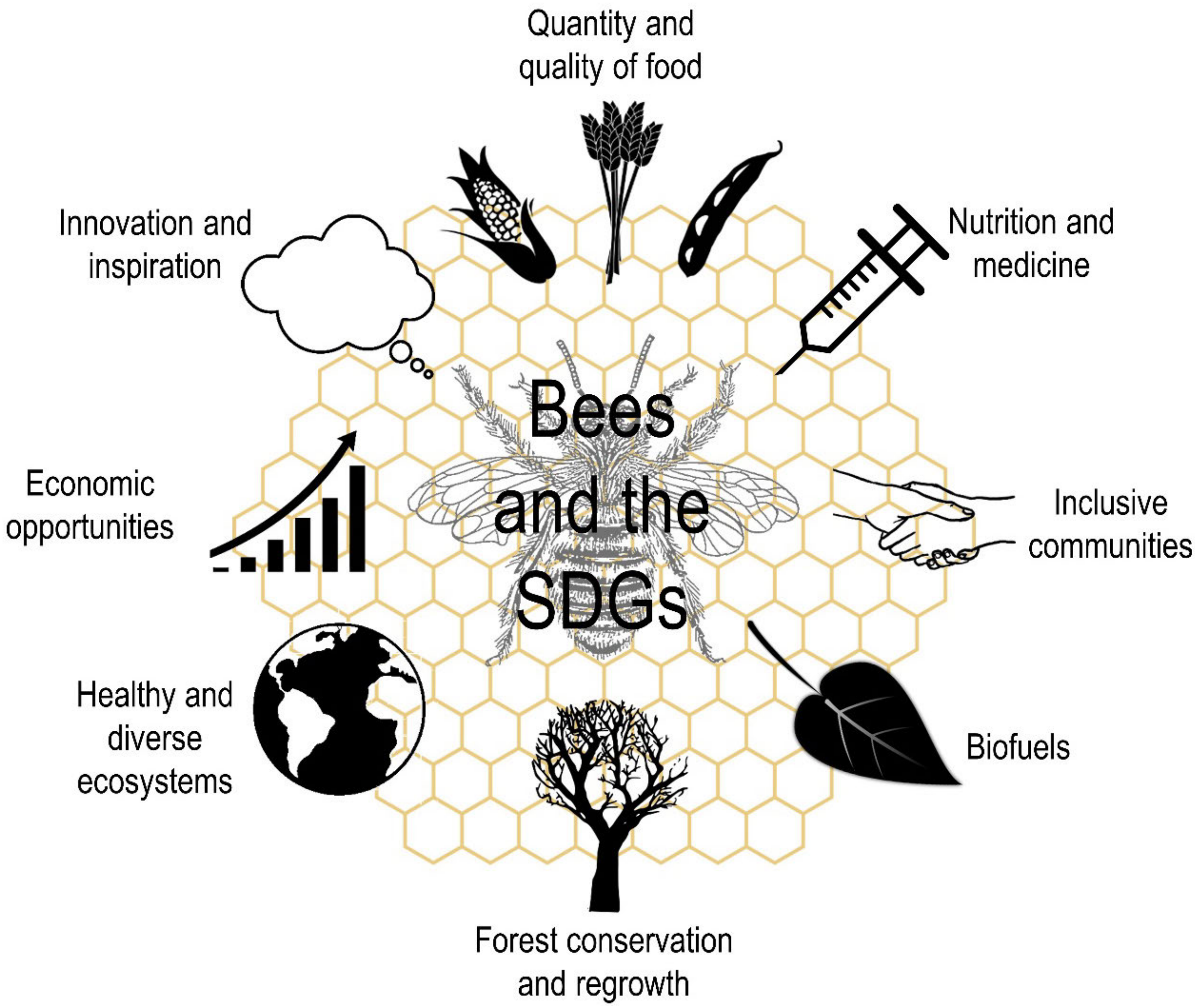

Figure 6: Bees and the SDGs. Overarching themes whereby bees contribute to sustainable development targets.

These themes provide a foundation for an emerging, yet urgently needed research agenda to explore the complex relationship between bees, people and the planet. The distinct roles of wild and managed bees provide a further research lens for identifying the critical role that bees can provide in achieving the SDGs. We must strive to restore balance and reverse bee decline trajectories if we are to encounter a future in which bees continue to contribute to the sustainable development of society.

Chapter 4. Using a social-ecological system approach to enhance understanding of structural interconnectivities within the beekeeping industry for sustainable decision making

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Abstract

The social-ecological system framework (SESF) is a comprehensive, multitiered conceptual framework often used to understand human-environment interactions and outcomes. This research employs the SESF to understand key interactions within the bee-human system (beekeeping) through an applied case study of migratory beekeeping in Western Australia (WA). Apiarists in WA migrate their hives pursuing concurrent flowering events across the state. These intrastate migratory operations are governed by biophysical factors, e.g., health and diversity of forage species, as well as legislated and negotiated access to forage resource locations. Strict biosecurity regulations, natural and controlled burning events, and changes in land use planning affect natural resource-dependent livelihoods by influencing flowering patterns and access to valuable resources. Through the lens of Ostrom's SESF, we (i) identify the social and ecological components of the WA beekeeping industry; (ii) establish how these components interact to form a system; and (iii) determine the pressures affecting this bee-human system. We combine a review of scholarly and grey literature with information from key industry stakeholders collected through participant observation, individual semi-structured interviews, and group dialog to determine and verify first-, second-, and third-tier variables as SESF components. Finally, we validate the identified variables

through expert appraisal with key beekeepers in the industry. Our results identify the governance system, actors, resource system, and resource units comprising the beekeeping industry in WA. Using this approach, we identify three principal system pressures including access to apiary sites, burning of forage, and climate change impacts on the system, which influence the SES and its sustainability. Our approach provides for an improved understanding of SES complexities and outputs that should be used to support improved sustainable management of common pooled resources to ensure effective pollination and sustained apiary production.

4.1 Introduction

Bees and beekeeping have recently received significant attention for their contributions to sustainable development (Carroll & Kinsella, 2013; Dangles & Casas, 2019; Klein et al., 2018; Minja & Nkumilwa, 2016; Patel et al., 2020; Vinci et al., 2018; Yap et al., 2015) and human well-being (Gill et al., 2016; IPBES 2016; Sánchez-Bayo & Wyckhuys, 2019;). Beekeeping involves the production of honey and other bee products as well as crucial pollination services (Pilati & Prestamburgo, 2016). For more than 15,000 years, the reciprocal relationship between Apis mellifera (the European honeybee[2]) and Homo sapiens has resulted in mutually beneficial outcomes (Lehébel-Péron et al., 2016), yet the interconnectedness between these two species has only been partially explored. Initial exploration of this relationship has used a social-ecological system (SES) approach to address resource management and sustainability of wild beehuman systems (Matias et al., 2017). Yet, to our knowledge, an SES approach has not been applied to managed bee-human systems, i.e., the beekeeping industry. The honeybee-human system is unique, and like those ecosystems supporting wild bee populations, it is equally vulnerable to adverse resource management decision-making (Aizen & Harder, 2009; Potts et al., 2010a; vanEngelsdorp & Meixner, 2010).

[2] In this paper, we use the word “bee” as shorthand to refer to the European honeybee, *Apis mellifera*. We recognize that there are approximately 20,000 described species of bee, of which 50 are managed species, the honeybee being one of them.

The sustainability of a beekeeping system depends on continuous access to quality forage resources for bees to maintain healthy and productive colonies (Pilati & Fontana, 2018). To access forage resources, many beekeepers, such as those in Europe and the United States of America, migrate their hives following honey flows across public and private lands (Durant, 2019; Pilati & Prestamburgo, 2016). Access to forage sites are often dependent on permission from authorities or through negotiation with private land owners (Hill et al., 2019). Ad hoc changes in management approaches on both private and public lands can limit access to important natural resources and impact beekeepers' livelihoods. Furthermore, because bee foraging is a landscape-scale process (Sponsler & Johnson, 2015), the impact of change in landscape composition is axiomatic in the case of migratory beekeeping (Evans et al., 2018; Galbraith et al., 2017; Malkamäki et al., 2016; Smart et al., 2016).

Complex natural and anthropogenic drivers are contributing to global bee decline (Goulson et al., 2015; Wagner, 2020) and are impacting on bee system contributions that support sustainable development (Patel et al., 2020). Evidence also suggests that negative interactions can occur between wild and managed bees, including resource competition, disease transmission, and plant-pollinator network disruption (Geslin et al., 2017; Mallinger et al., 2017; Valido et al., 2019). As global agricultural landscapes have become less diverse and increasingly reliant on pollinators (Aizen et al., 2019), a rise in the number of managed bee colonies has occurred to cope with the pollinator deficit (as highlighted in Aizen and Harder, 2009). As a result, an increase in interactions between domestic and with wild bee populations may occur. However, safeguarding both wild and managed bees is critical for food production and to address wider sustainability challenges, targeted approaches that adopt a bee-human system perspective (Kleijn et al., 2018; Patel et al., 2020; Saunders et al., 2018,) are required. Bee-human system sustainability implies maintaining broader bee biodiversity to ensure a sustainable supply of bee mediated services (Patel et al., 2020).

A social-ecological systems approach provides a lens through which the bee-human relationship can be examined. To date, research has primarily focused on the benefits humans receive from bees (Bradbear, 2009, Carroll and Kinsella, 2013, Klein et al., 2018) rather than the reciprocal relationship between the two species. Using an SES framework, both human and natural systems can be examined in equal depth (Binder et al., 2013), providing a mechanism for understanding the complex interdependencies between the various components of both systems. Importantly, the complex feedbacks between social and ecological components contribute to the management of ecosystem service (ES) flows (Rova & Pranovi, 2017). Applying an SES approach to the bee-human system allows for the identification and management of system drivers, activities, and processes that contribute to the sustainable development of the system (Matias et al., 2017) through improved environmental management and governance (Rodela et al., 2019). As such, our research aim is to characterize the beekeeping industry as an SES through identification of human and biophysical components, associated interactions, and key beekeeping processes. Acquired novel understanding of the complex interconnectivities associated with the beekeeping SES will enable facilitated management of system pressures, i.e., the availability, access, and utilization of apiary sites, and help inform integrated policy design to achieve sustainable development that is inclusive of biodiversity conservation.

4.1.1 Social-ecological system framework (SESF)

In this research, we focus on conceptualizing beekeeping as a social-ecological system through the lens of Elinor Ostrom's SES framework (SESF; McGinnis and Ostrom, 2014), using the beekeeping industry of Western Australia (WA) as an applied case study. Ostrom's SESF was primarily designed for application to management situations in common pool resources where humans are accountable for sustainable extraction and maintenance of resources (McGinnis and Ostrom, 2014, Rodela et al., 2019). The framework represents a hierarchy of multitiered interacting components under six core concepts representing the first tier; resource systems (RS), resource units (RU), governance systems (GS), actors (A), interactions (I), and outcomes (O). The core concepts are nested within the broader social, ecological, and political setting (S) accounting for feedback from, to, and between other ecosystems (McGinnis & Ostrom, 2014; Ostrom, 2009; Ostrom & Cox, 2010). Each core concept is decomposable into a number of lower tiers, which can dictate local data collection (Hinkel et al., 2015; Ostrom, 2009; Partelow, 2016) for monitoring and guiding management of the system.

Ostrom's SESF has been applied to resource sectors such as forestry, irrigation, agriculture, fisheries, and watershed management (Partelow, 2018). Although the framework represents bidirectional links between social and ecological systems, variable development in SESF applications has disproportionately focused on social system variables (Partelow, 2018), with fewer applications adding ecological system variables (Vogt et al., 2015). Additionally, limited research has identified variables for local-level analysis (Delgado-Serrano, 2015), those that have targeted variables to match with common terminology of the application being studied, such as socio-technical systems(Acosta et al., 2018). The uniqueness of some lower tier variables to specific sectors requires sector-specific SESFs (Basurto et al., 2013; Partelow, 2018), either developed vertically by adding lower tiers under existing concepts, e.g., sea-bed tracts as a lower tier within benthic small-scale fisheries (Basurto et al., 2013), or horizontally by adding sector-specific first tier concepts, e.g., addition of transformation systems and products specific to food systems (Marshall, 2015). In either approach, defining each variable relevant to the sector can improve transferability of the SESF.

Following conceptual guidance provided by Hinkel et al. (2015) and ontological logic suggested by Frey and Cox (2015), we focus on applying Ostrom's SESF for the beekeeping sector using migratory beekeeping in WA as an applied example. We advocate that our approach can be used to improve environmental management through identification of key processes involving human and biophysical components, to help ensure the long-term sustainability of the bee-human system. Our research identifies the key interactions important for understanding how various pressures can manifest across the bee-human system. To address the research aim, we explore the following questions: (i) what are the social and ecological components of the beekeeping industry; (ii) how do these components interact to form a system; and (iii) what pressures are affecting the bee-human system? We achieve this through application to the beekeeping industry of WA.

4.2 Methods

4.2.1 Study location: Western Australia

The beekeeping industry of WA is characterized by clean and healthy colonies of the European honeybee (*Apis mellifera*), devoid of the pests and diseases that affect bee health in nearly all other parts of the world (Chapman et al., 2008; Gordon et al., 2014). Although the European honeybee is an introduced species in WA[3], the beekeeping industry relies on native flora, especially eucalypt species, across a mosaic landscape of forest, woodlands, shrublands, and heathlands (Arundel et al., 2016; Benecke, 2007). Australia has a diverse native bee fauna, and concerns have been raised as to whether introduced honeybees may compete with native bees for floral resources and/or nesting sites, or affect reproduction in native plants (Paini & Roberts, 2005). A recent global review identified a range of evidence detailing adverse effects of managed bees on native bees (Mallinger et al., 2017), but within Australia there is insufficient evidence available to evaluate whether *Apis mellifera* has broad adverse effects on native bee species' survival or reproduction (Batley & Hogendoorn 2009, House of Representatives Standing Committee on Primary Industries and Resources 2008, Paini, 2004). Because the European honeybee has been managed and naturalized in Western Australia for many decades, it is possible that the initial wave of adverse ecological effects has passed undocumented.

[3] Acknowledging that the European honeybee is a non-native species in Western Australia, in this paper we consider only managed honeybee colonies and do not consider feral honeybees. Feral bees have a suite of associated conservation issues including taking over suitable nesting hollows for native birds, mammals, and reptiles (Gibbons & Lindenmeyer, 2002; Johnstone et al., 2013).

The majority of WA's honey-producing landscapes are geographically restricted to the Southwest Australian Floristic Region (SWAFR; Benecke, 2007; Gibbs & Muirhead, 1998; Roshan et al., 2017; Smith, 1969). Changes in weather and life stages of flora and fauna across the region are best characterized using the six seasons described by the traditional custodians of the land, the Noongar (Figure 7). Specifically, forested areas are sought after for polyfloral and monofloral honey production. In WA, forest and woodland stands dominated by jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) are coveted for monofloral honey production, given higher revenue potential because of the honey's unique flavor, texture, and medicinal properties (Roshan et al. (2017), Soares et al. (2017); Figure 7).

Apiarists in WA migrate their hives between two to six times per year following the sequence of flowering events across the state (because the timing of peak flowering varies with species and location), traversing a mix of private and leased public sites in the process (Gordon et al., 2014; Somerville & Nicholson, 2005). Usage of each site lasts between two weeks and a few months depending on variability in active flowering and nectar production. The success of each migration sequence is dependent on the quality of the individual site accessed (Pilati & Prestamburgo, 2016; Somerville & Nicholson, 2005). Foraging resources are primarily located on government-managed land, including state forest, national parks, and nature reserves, which together account for more than 75% of the state's honey production (Crooks, 2008; Gibbs & Muirhead, 1998). Over the past decade, 31% of beekeepers have reported reductions in the use of public land because of restricted site access in response to changing government policies (van Dijk et al., 2016).

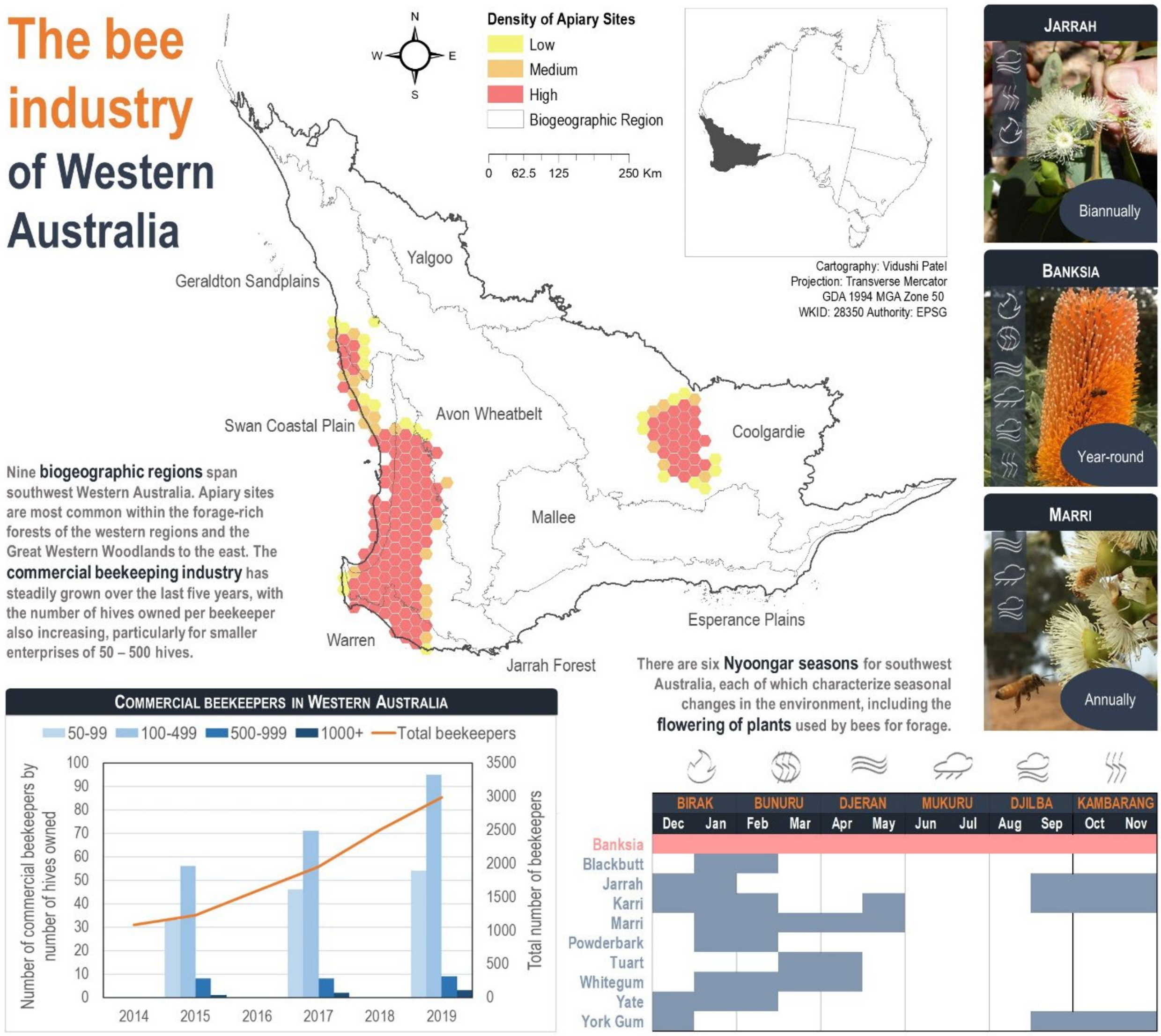

Figure 7: The bee industry of Western Australia indicates an increasing temporal trend in both the total number of beekeepers and those practicing commercially (beekeepers who own > 50 hives; graph). However, state production is constrained to the Southwest Australian Floristic Region (SWAFR), where there is a high density of permits issued for apiary sites (map). Beekeeping is migratory, following the year-round availability of high quality forage species (chart: species are Banksia, or eucalypts from the genera Eucalyptus and Corymbia), with jarrah, marri, and Banksia (photos) the key species targeted by Western Australia beekeepers. There are 60 species of Banksia in the southwest region, with varying flowering phenologies; beekeepers rely on Banksia species during times when eucalypts are not flowering. Data were sourced from the Department of Biodiversity Conservation and Attractions (apiary sites), Interim Biogeographic Regionalisation for Australia (used to delineate biogeographic regions), Australian Bureau of Statistics (state boundaries), and Bureau of Meteorology (used to identify Noongar flowering calendar).

The beekeeping industry is growing rapidly in WA. Similar to all livestock owners, beekeepers are required to register with the Department of Primary Industries and Rural Development (DPIRD). According to data sourced from DPIRD, between 2015 and 2019 the total number of registered beekeepers more than doubled, with a 64% increase in commercial beekeeping (defined as more than 50 hives) over the last five years (Figure 7). Demand for forage sites to host apiaries has also increased responding to industry growth. As of 2018, 4479 site licenses were made available by the Department of Biodiversity Conservation and Attractions (DBCA), and of these, 70% were located within the SWAFR (Figure 7).

Although sites on private land are often used for free or in exchange for honey products, sites on public land require the issue of a lease (subject to renewal every seven years) and vegetation clearing approvals (if clearing is required). Beekeepers request a permit from DBCA to site their apiaries. The requested site coordinates are then sent to the relevant local government for assessment against a series of criteria before sanctioning an apiary permit for hive placement within 500 m from the approved coordinates. Reporting the duration of site use to DBCA is mandatory for monitoring resource use. Spatial overlap of apiary permits with other land tenure may result in additional negotiation with existing lease owners (Salvin, 2015), which adds a multifunctional aspect to resource management for beekeeping.

In addition to managing resource access, the beekeeping industry is facing numerous challenges. There is an increasing risk of pest and disease attacks (Crooks, 2008; Phillips, 2014) despite strict biosecurity regulations. Extensive agriculture and urbanization have resulted in the removal of nearly 80% of the extent of native vegetation in southwest WA since 1910 (Andrich & Imberger, 2013; Phillips et al., 2010; Shedley et al., 2018). Land clearing has likely contributed to reduced precipitation (Andrich & Imberger, 2013; Pitman et al., 2004) and altered groundwater levels (Dawes et al., 2012), which have adversely affected the biodiversity of the region (Brouwers et al., 2013; Mastrantonis et al., 2019). The declining trend in precipitation since 1970 is projected to continue into the future (Hughes, 2011; Pettit et al., 2015; Smith & Power, 2014), which has implications for survival and distribution of forage resources. For example, drought can have an adverse impact on the growth and flowering of melliferous (nectar-producing) flora (Benecke, 2007). Soil-borne Phytophthora dieback is affecting important species used to produce honey, such as karri (*Eucalyptus diversicolor*) and jarrah (Benecke, 2007). And last, changing land regulations such as an increase in conservation areas has affected beekeepers' access to their traditional resource base (Benecke, 2007).

Given these collective challenges, there are many necessary critical management and governance considerations to ensure the long-term viability of the ecosystem services obtained from beekeeping activities while conserving broader biodiversity. Characterizing the WA beekeeping industry using Ostrom's SESF is a step toward providing a more informed bee-human structural framing to support collective action (Phillips, 2014) and a transition toward strategic environmental decision making (Elsawah et al., 2015; McGinnis & Ostrom, 2014; Partelow et al., 2019).

4.2.2 Employing the SESF for the beekeeping industry

Identifying and defining important SESF variables and feedback amongst variables required a mixed-methods approach. We conducted qualitative research following a diagnostic procedure suggested by the SESF literature (Hinkel et al., 2015; Ostrom & Cox, 2010; Partelow et al., 2018a) to prepare an initial list of second tier variables that built upon the first tier concepts (Figure 8) for the beekeeping SES. Although literature to guide the variable development process was scant (Partelow et al., 2018b), sufficient information from other applications of the framework was available to guide direction of the SESF for establishing multitier variables (Delgado-Serrano & Ramos 2015; McGinnis & Ostrom 2014; Ostrom 2009; Vogt et al., 2015), build ontology for new concepts (Frey & Cox, 2015), and apply to the bee-human system (Acosta et al., 2018; Johnson et al., 2019; Nagendra & Ostrom, 2014; Ovitz & Johnson, 2019; Partelow et al., 2018b). The initial literature-informed list was further refined and updated to include third and fourth tier variables, and subsequently validated using various local stakeholder engagement activities.

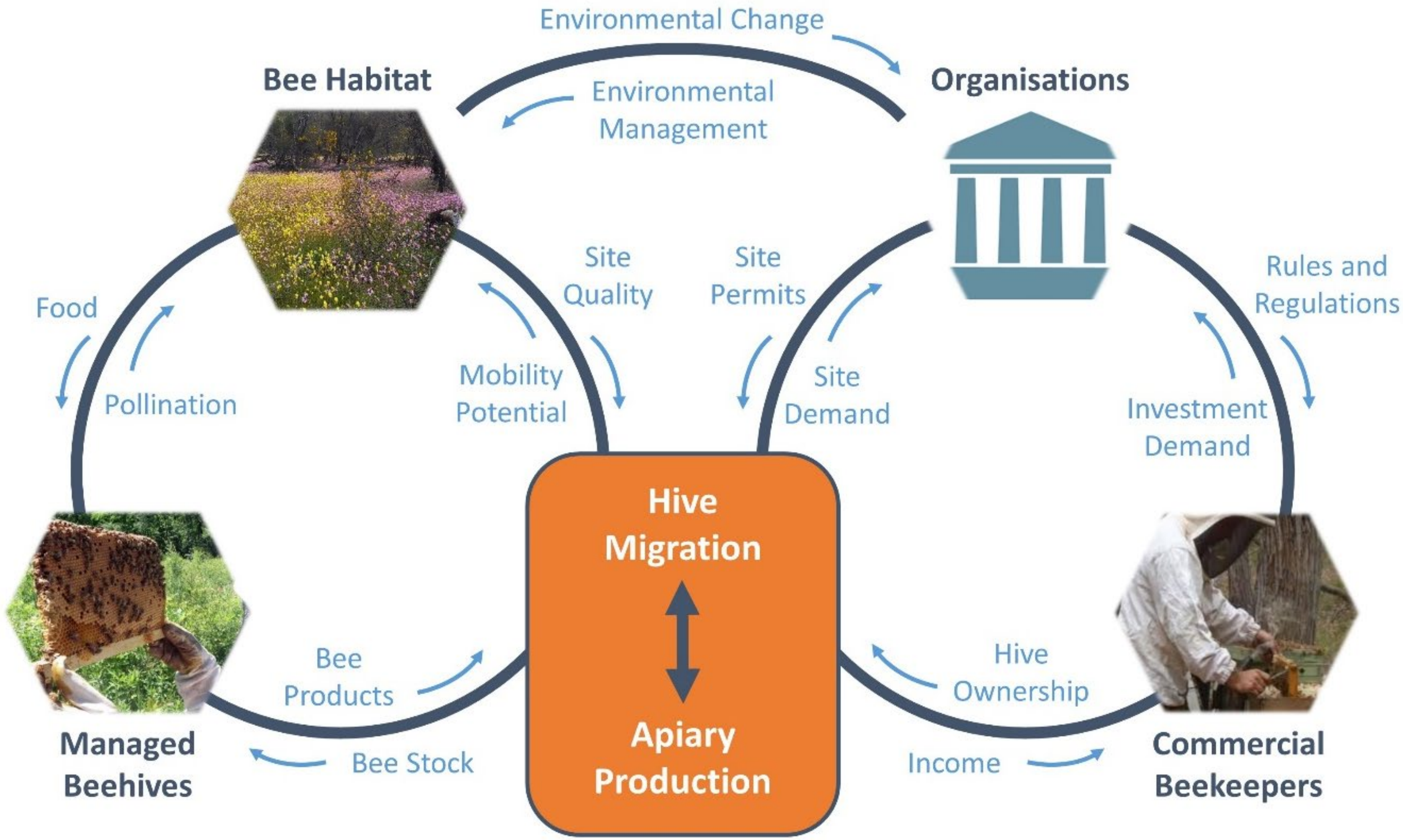

Figure 8: Conceptual diagram of the social-ecological system for the beekeeping industry guided by Ostrom (2009). This illustrates the Tier 1 components of the social-ecological system framework, comprising bee habitat (resource system), managed hives (resource unit), organizations (governance system), commercial beekeepers (actors), hive migration (interactions), and apiary production (outcomes).

For each phase of data collection, key SESF literature including McGinnis and Ostrom (2014), Delgado-Serrano and Ramos (2015), Hinkel et al. (2015), Vogt et al. (2015), and Partelow, (2018) was used to guide the collation and refinement of SESF variables. Further details on references and methods for each SESF variable, which was ultimately defined, are provided in Appendix 3.

4.2.2.1 Preparing the initial list of variables

To prepare the initial list of variables, a desktop analysis of government reports, news articles, policy documents, and relevant industry communications was conducted, and key terms were listed under each first tier concept. For example, tree plantation, native forest, and weeds on roadsides were listed under "Resource System" from government reports on commercial beekeeping in Australia (Benecke, 2007; Goodman, 2014). Similar to (Phillips, 2014), participant observation, collected through attendance at meetings of beekeeping organizations, conferences, and industry organized community engagement activities, was used to list additional terms under each concept. Archival and observational assessment information was then cross-referenced with other applications of the SESF applications such as fisheries (Basurto et al., 2013; Leslie et al., 2015) and aquaculture (Partelow et al., 2018b) so that the listed terms could be identified as an existing variable or a new variable. To refine the variable list, semi-structured interviews with key industry stakeholders were conducted. Verification of variables was then performed with industry experts within a focus group discussion session. Following verification, variables were independently validated by expert retired beekeepers within a focus group discussion session. This process of variable refinement, verification, and validation followed a multimethod iterative stakeholder engagement approach (outlined in Table 2), similar to that used by Johnson et al., (2019).

4.2.2.2 Refinement of the initial list of variables

For variable refinement using semistructured interviews with key industry stakeholders, participants were recruited using a snowballing technique centered on circulation of a volunteer request flyer via social media, word of mouth, and through advertisement by the Beekeeping Industry Council of

Western Australia (BICWA). Using a similar approach to Malkamäki et al. (2016), two question guides were developed, reflecting the broad themes identified through the initial variable preparation process (Appendix 4), and used to conduct semi-structured interviews (duration: 35–50 minutes) during 2017 and 2018 with 29 commercial and semicommercial beekeepers. This participant sample represents approximately one-fifth of the beekeeping industry in WA[4] who are major contributors to the total honey production of the state. Sampling was stopped upon saturation where no additional information was collected from participants. Two representatives from governing organizations were also interviewed. All 31 participants provided written consent for undertaking the interviews.

Table 2: Summary of methods used to seek information from stakeholder groups to inform the development of a social-ecological systems framework for the beekeeping industry in Western Australia.

Stakeholder group	Number of participants	Method used	Duration	Outcome
Full time beekeeper Part-time beekeeper	14 15	Semi-structured interviews	35 – 40 minutes	Refinement of initial SESF variable list
Government officials	2	Semi-structured interviews	30 – 35 minutes	Refinement of initial SESF variable list
Research experts actively working on vivid aspects of the bee industry	4	Open-ended discussion	2.5 hours	Verification of the refined SESF variable list relevant to the bee industry
Retired beekeepers	6	Workshop Mind mapping	5 hours	Independent validation of the SESF variable list relevant to the bee industry Identification of key feedbacks within the bee industry-SES Identification of key pressures and their potential effect on the bee industry-SES

[4] In this paper we define the beekeeping industry to represent commercial (apiarists managing more than 500 hives) and semi-commercial beekeepers (apiarists managing between 50 and 500 hives) in WA.

4.2.2.3 Verification of refined variables

Experts actively engaged with the beekeeping industry in WA were asked to form part of an advisory group[5]. An open-ended discussion session was conducted with the advisory group members regarding the initial and refined lists of variables. Different approaches for open-ended discussion were used because of time commitments of the members; four members met with the lead researcher together in a group setting, and the remaining two members met with the lead researcher individually (during October 2018).

4.2.2.4 Validation of variables and identification of key feedback within the system

Because experienced beekeepers hold deep local knowledge of bee systems (Galbraith et al., 2017; Uchiyama et al., 2017), a full day workshop was conducted with six retired beekeepers (December 2018; Figure 9), whose involvement in beekeeping spanned 30 to 60 years, to undertake independent validation of the verified SESF (Stojanovic et al. (2016); note, active commercial beekeepers with similar experience were unable to commit for the day-long workshop). This validation stage was independent because no leading information was provided to participants. A professional moderator was used to mediate the activities to avoid researcher bias in the process (Knapp et al., 2011). The first activity of the workshop required participants to list all environmental and human aspects deemed necessary to the functionality of the beekeeping industry. Subsequently a mind mapping exercise was performed to harness key interconnectivities across the industry. To refine the initial mind map further, discussion was prompted using 30 keyword cards covering broad SESF themes (e.g., "plants"); this was to ensure participants had considered all the system components for which validation was required. Any discussion by participants concerning system pressures was listed throughout the workshop by a second session moderator who did not engage in the workshop adjudication (this was the lead investigator). Following the mind map

[5] Five members were selected to form the advisory group based on an individual's reputation within the beekeeping industry and ensuring a diverse representation of stakeholder groups, which included government agencies, private businesses, research institutions, and beekeeping organizations.

generation, the lead moderator then requested participants to add any system pressures that had been noted by the second moderator to the system mind map; an open discussion then refined these ideas. After all four activities were completed, participants were invited to ask questions to the lead investigator and lead moderator regarding the broader objectives of the research.

Figure 9: Retired beekeepers sharing their knowledge in the mind mapping session for validating social-ecological systems framework variables for the beekeeping industry. Green sticky notes were used to list environmental aspects, yellow for human aspects, and blue for key pressures.

4.3 Results

In total 168 SESF variables for the WA beekeeping industry were identified, including 56 second tier, 72 third tier, and 32 fourth tier components (Figure 10, Appendix 3). Further details on each of the SESF components are provided in the following sections.

4.3.1 Core subsystems

The core subsystems (Tier 1 variables) of the WA beekeeping industry included the Resource System (RS), Resource Units (RU), Actors (A), and Governance System (GS), as described following the variable list provided in McGinnis and Ostrom (2014; Figure 8). Below we outline some of the first, second, third, and fourth tier variables to provide a narrative to support Figure 10 and the complete list in Appendix 3.

4.3.1.1 Resource System (RS)

The landscape of bee resources (melliferous flora) forms the resource system for the beekeeping SES. Bee visitation of flora in various land uses such as forest (RS1a), agriculture (RS1b), or other plantations (RS1c) exhibit variable outcomes and access regulations. Setting apiaries within the forest boundary (RS2a) requires the maintenance of 3 km separation distance from other apiaries (RS2c). However, inapplicability of this mandate on private land across fence boundaries (RS2b) further highlights the position of human-constructed facilities (RS4) in accessing resources. Beekeepers have reported determining productivity of the forage landscape (RS5) according to spatial and seasonal variability of flowering events (RS7), location and association (RS9) of species, and information related to previous system disturbances (RS8). For instance, landscapes with high diversity forage species are reported to have longer flowering events, leading to healthy bees and higher yield with less travel. Additional RS variables at second and third tiers, as proposed by Vogt et al. (2015), include ecosystem histories (RS10) specific to natural disasters (RS10a) such as drought or bushfire (RS10b), and were included in the initial list and validated during the variable refinement process.

4.3.1.2 Resource Unit (RU)

Following the diagnostic questionnaire proposed by Hinkel et al. (2015), the Resource Unit (RU) is identified as the managed bee colony because it is involved in the generation of benefits from the SES and depends on the RS to survive and thrive. Mobility of beehives (RU1) is critical in migratory beekeeping, where maintaining healthy and productive colonies (RU2) is the prime interest of the beekeepers (Pilati and Prestamburgo 2016, Pilati and Fontana 2018). Beehives are managed for honey production (RU5a) and for crop pollination (RU5b). Based on the total number of hives managed by a beekeeper, a load (approximately 100 hives can be transported by one flatbed truck) of hives (RU5ai) was added as a fourth tier variable. Load size and their spatial and temporal placement (RU7) depend on forage availability; for example, insufficient forage availability could result in splitting a load into smaller sizes (30–50 hives) but increases transport costs to accommodate their spatial-temporal arrangement. The value of beehives (RU4) was categorized as a market value (RU4a), environmental value (RU4b), and strategic value (RU4c; Delgado-Serrano & Ramos, 2015). The condition of the RS and RU are the most important factors contributing to social-ecological system sustainability (Frey, 2016), and inter/ intraspecific interactions (RU3a/RU3b), including spatial proximity (RU3ai) of the resource units. Marking each hive (RU6a) with a registered brand is mandatory for all beekeepers in WA.

4.3.1.3 Governance system (GS)

Government organizations (GS1) that manage and monitor bee resources, e.g., DBCA, and bee stock, e.g., DPIRD, directly interact with beekeepers and operational activities at state-level organizations (GS1b) as well as the local government-level (GS1c). Contributions from research organizations (GS2b) were found to improve the beekeeping industry with 74% of beekeepers in Australia experiencing up to 25% increase in production by changing their management practices as a result of research (van Dijk et al., 2016). Based on sectoral research funding, fourth tier SESF variables were added for academic research (GS2bi), industry-funded research (GS2bii), and cooperative research centers (GS2biii). Social connections between beekeepers and land owners/managers (GS3a) and within beekeeper groups (GS3ai) are a key influencing factor regarding resource access and use, irrespective of the governing rules (GS5-7) because of an increasing reliance on private land. Conflict between beekeepers (I4a) can also be related to GS3a and GS3ai, as identified by several apiarists. In addition, constitutions related to beekeeping (GS7a), biosecurity (GS7b), access to resources (GS7c) including forest management (GS7cii), local government bylaws (GS7ciii), and food handling requirements (GS7civ) influence monitoring and sanctioning rules (GS8a-b) at a local level, and were added as fourth tier variables.

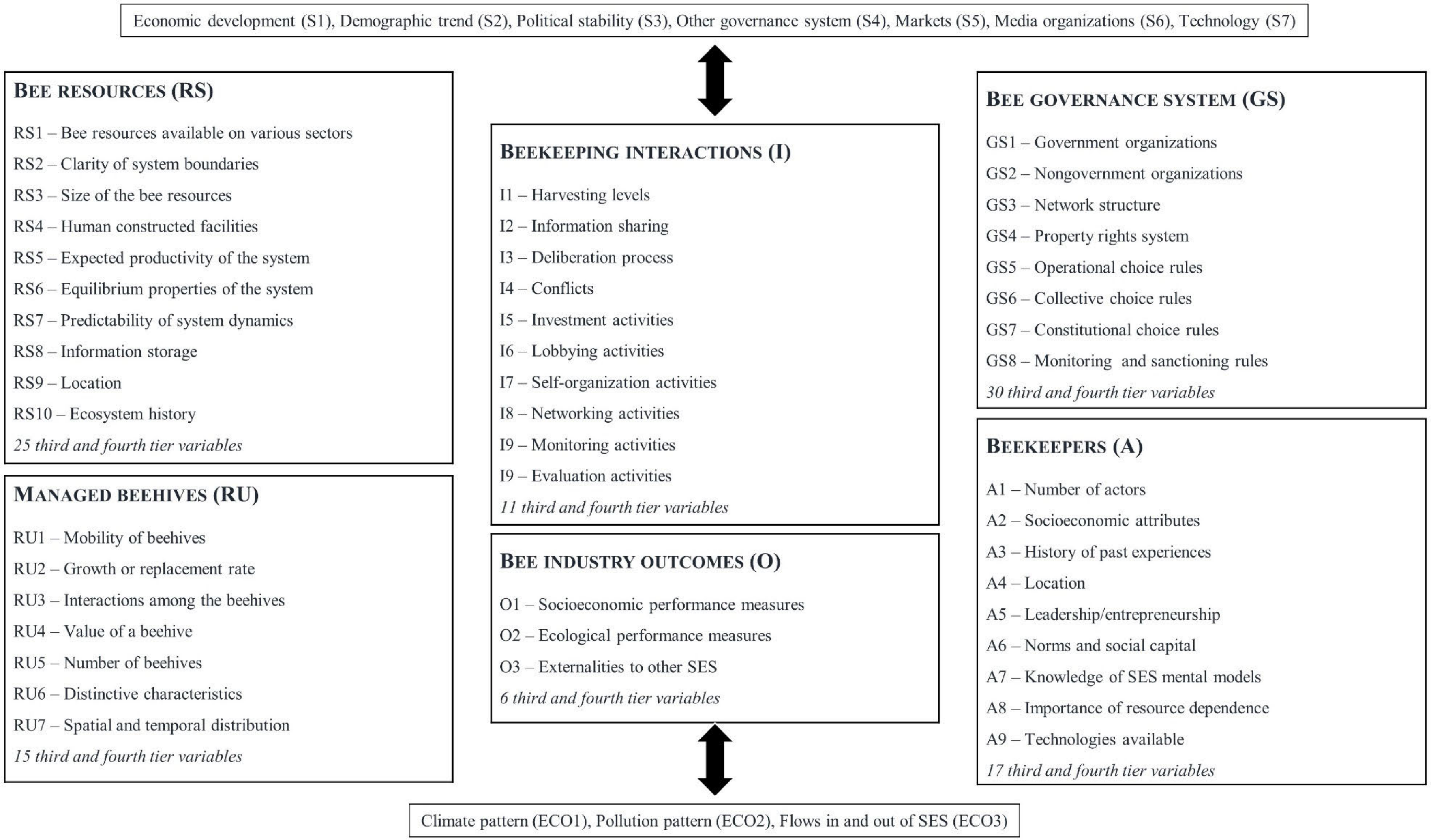

Figure 10: First and second tier social-ecological systems framework (SESF) variables that define the beekeeping industry in Western Australia. Third and fourth tier variables are provided in Appendix 3.

4.3.1.4 Actors (A)

Migratory beekeepers are the key actors (A) in the bee-human system. Age and intergenerational involvement in beekeeping are key demographic attributes (Galbraith et al., 2017; Phillips, 2014) that determine experience (A3) and local ecological knowledge (A7a). Based on diverse economic characteristics (A2b), four fourth tier SESF variables were identified: large-scale operators (> 499 hives; A2bi), small-scale operators (50–499 hives; A2bii), equipment manufacturers/suppliers (A2biii), honey packers, and queen bee breeders (A2biv). All large-scale operators were fulltime beekeepers (A8a) with total dependence on beekeeping for their livelihoods. Intergenerational beekeepers followed the knowledge of their parents and grandparents regarding the rich spatial-temporal history of resources, production, weather, and issues at their regular forage sites, and were also involved in sharing beekeeping knowledge by training new beekeepers (A5b). For other commercial and semicommercial beekeepers, a general transition of hobbyists from part-time (A8b) to full-time (A8a) beekeeping was observed. Various levels of technology (A9) were reported including mobile phone and internet to access information, and use of satellite imagery and other advanced sensor-based devices for hive resource monitoring; these were dependent upon the scale of operation, age of the beekeeper, and aspiration for future expansion.

4.3.1.5 Focal action situation: Key Interactions (I) and Outcomes (O)

Information sharing (I2) concerning forage resources was reported as a main form of interaction between beekeepers. The state-level beekeeping organization (BICWA) is involved in deliberation (I3) and investment activities (I5) for the industry and has representatives from formal beekeeper groups (I2a) including hobbyists (WA apiarist society), semicommercial and commercial (WA beekeeper association, WA farmer federation), and the committee of producers (Agriculture Produce Commission). Additionally, there are known informal beekeeper groups (I2b) with various levels of interaction.

Several conflicts were included as SESF variables because they were identified by the majority of participants as affecting governance of the bee-human system. Conflict between beekeepers (I4a) can arise where one beekeeper is seen to harvest resources from another beekeeper's patch; generally by placing hives on the edge of private land next to forest. Such situations may unfold due to noncompliance of the 3 km apiary separation regulation on private land (RS2c). Close colony proximity can also inadvertently increase biosecurity risk through compromised hive health (e.g., disease transmission), potentially leading to a loss of hives. In addition, loss of bees due to use of fungicide by a farmer hiring beehives for pollination services was also identified as a point of contention (I4b). Conflict also exists between regulatory authorities, e.g., DBCA, and beekeepers regarding loss of forage resources due to land management practices, such as prescribed burning (I4c).

Harvests vary by beekeeper (I1a) and depend on the number of hive holdings, knowledge, and access to forage resources and other socioeconomic attributes. Different forage locations (I1b) lead to variability in yield (quantity) and quality as a result of vegetation mix and health. Resource monitoring activities (I9a) carried out by beekeepers are based on monitoring rules (GS8) developed by government organizations (GS1) and influence hive migration patterns and expected productivity of forage sites (RS5). However, decision making for migration of beehives also depends on the growth and replacement rate (RU2) of the hives, hence, beehive monitoring activities (I9b) was added as a variable under monitoring activities.

When beekeepers do not receive payment for pollination, it is considered an externality (O3ai) of the system flowing to agriculture and forest systems alike (IPBES, 2016; Siebert, 1980). Combining beekeeping with other industries, e.g., api-tourism in Slovenia, can have multiplier effects on regional economies and support improved management (Arih & Korošec, 2015; Gemeda, 2014). Packaging industries (O3aii) was added as a positive externality. Resource competition with other species (O3bi) and potential for disease transmission (O3bii) through migratory practices was identified as a negative externality (O3b). Interaction between bees and beekeepers (I9b) is integral to beekeeping activities and affects overall beehive migration patterns. For example, beekeepers managing a large number of hives tend to visit a number of sites across the state, and move greater distances from their home location, when compared to a small-scale, part-time beekeepers.

4.3.2 Sustainability pressures

Key pressures that affect the sustainability of the WA bee-human system were identified. Responses to interview questions related to issues and pressures (see Appendix 4) with beekeepers and government representatives were analyzed to calculate how many participants mentioned each pressure (see Table 3). All listed pressures were independently validated by the retired beekeepers group except for "backward in technology usage."

Table 3: Pressures on the Western Australia bee-human system according to the number of people in each stakeholder group who mentioned each pressure.
Retired beekeepers independently validated pressures during a collective workshop, hence their responses are noted as a binary yes-no.

Pressure	Beekeepers (*n*=29)	Government representatives (*n*=2)	Retired beekeepers (*n*=6)
Availability/access to forage sites	18	1	√
Burning of forage resources	17	1	√
Climate change	12	1	√
Lack of rainfall and/or declining water table	10	0	√
Land use / land cover change	9	0	√
Biosecurity	8	2	√
Logging	4	0	√
Underutilization of sites	3	1	√
Variability in flowering	3	1	√
Government (in)action	3	0	√
Hive theft and vandalism	2	0	√
Spraying of fungicides and insecticides	2	0	√
Lack of communication	2	1	√
Cheap honey	1	0	√
Backward in technology usage	1	0	
Lack of authority to monitor sites	1	2	√

The three top pressures mentioned by stakeholders were (i) availability, access, and utilization of apiary sites, (ii) burning of forage resources, and (iii) climate change. These pressures were mentioned by the majority of interviewees and focus group participants and received consensus in all stakeholder engagements (see Table 3).

4.4 Discussion

Global bee decline and its likely consequences for human wellbeing are increasingly being recognized (Gill et al., 2016; Potts et al., 2016b; Klein et al.; 2018). A multitude of natural and anthropogenic factors have been attributed to this decline, including depletion of forage resources (Durant, 2019; Goulson et al., 2015). Although forage scarcity results from both natural (e.g., phenological mismatch) and anthropogenic (e.g., land use change) factors, effects of forage scarcity is detrimental to all bee populations and could potentially contribute to resource competition between wild and managed bees. A clearer understanding of bee-human systems can provide a potential pathway to better manage ecosystem services delivered by managed bees (Gill et al., 2016; Klein et al., 2018; Matias et al., 2017; Patel et al. 2020; Potts et al. 2016).

We have described the first application of the SESF to the beekeeping sector, enabling us to understand the structural interconnectivities within the beekeeping SES and the challenges that threaten the sustainability of the system. Decision makers can use our SESF to direct management operations for minimizing trade-offs and maximizing synergies for system components to work toward optimized system functionality. We provide insights to illustrate potential use of our SESF by showcasing three examples that relate to the top three system pressures identified during the data collection process. The SESF can provide a structured response mechanism for enhancing environmental management of the beekeeping industry and guide sustainable decision making for managing system pressures, including those that are under immediate control of state policy makers, e.g., forage access or burning of resources, and also those that require long-term systematic change, e.g., climate change or rainfall shifts.

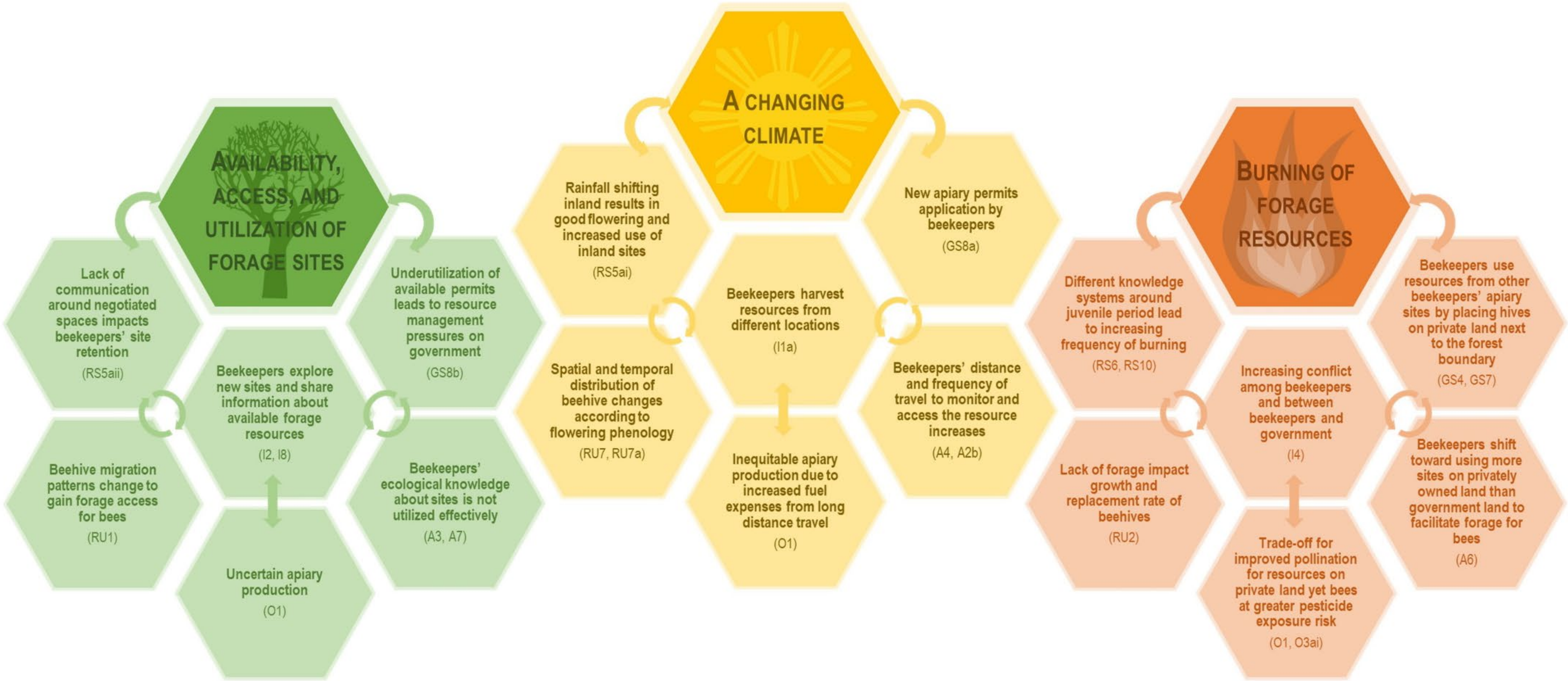

Figure 11: The impact of the priority pressures on the beekeeping social-ecological system (SES) in Western Australia Priority pressures of (i) availability, access and utilization of forage sties, (ii) a changing climate, and (iii) burning of forage resources. Each diagram indicates the impact of the pressure on various components and example feedback pathways within the beekeeping social-ecological system (SES) in Western Australia (refer to Appendix 3 for variable coding). The diagrams are formatted to match the SES framework core components illustrated in Figure 8.

4.4.1 Addressing priority bee-human system pressures

Changes affecting bee-human systems are generally socio-cultural, environmental, economic, and governance-oriented in nature (Matias et al., 2017). Sustainability of the beekeeping industry depends on continuous access of quality forage sites (Pilati & Prestamburgo, 2016). Challenges such as decreasing resource access and biosecurity risks have been previously documented for the Australian beekeeping industry (Phillips, 2014), and reinforced through our data collection. To address key pressures using the SESF, interconnectivities where synergies and trade-offs occur are illustrated in Figure 11. This provides insights into the elements and feedback processes contributing to the top three pressures (discussed in the following section) identified for the WA beekeeping industry.

4.4.1.1 Availability, access, and utilization of apiary sites

In migratory beekeeping, sustainability varies according to the sequence of apiary sites accessed by a beekeeper (Pilati & Prestamburgo, 2016). Beekeepers' access to forage sites depends on a range of factors including biophysical conditions (e.g., blocked physical access due to vegetation growth), legislation (e.g., burning regimes), negotiations (e.g., with land owner or existing lease holder), changing land management practices (e.g., approval of new walking trails; RS5ai), and change in individual practice (e.g., upgrading truck size limits access to sites only accessible with smaller vehicles). The importance of forage locations with high species diversity (Coh-Martínez et al., 2019) and increasing variability in flowering events cause full-time beekeepers to maintain a number of underused sites as backup (Figure 11). In addition, technological progress in management initiatives also contributes to variability in SESs; for example, in WA, an online portal designed to ease the apiary permit process has been attributed to increasing vandalism and hive-theft after apiary site locations were made available online.

A national level policy change can also add to SES variability. For example, revising the regulation of holding permits per number of hives, under the National Competition Legislation (CALM, 1997), has resulted in conflict among beekeepers because of withholding apiary permits for earning rent rather than providing forage. This underuse of resources (Mauerhofer et al., 2018; Miyanaga & Shimada, 2018) requires beekeepers to find new sites, and change hive migration patterns (RU1), leading to uncertain apiary production (O1). Such situations can result in increased resource management pressure on the government (GS8b). In addition, conservation initiatives, aimed at limiting the interactions of managed bees with natural ecosystems, can also affect a beekeeper's access to resources. The issue of availability and access to resources largely contributes to SES sustainability (Frey, 2016) and requires an understanding of the nonlinear nature of SES interactions in order to avoid siloed decisions. Key variables and interactions identified in this research provide the basis to guide integrated decisions toward sustainable resource access for bee-human systems.

4.4.1.2 A changing climate

Beekeeping activities are heavily influenced by climatic conditions, including rainfall and temperature. A positive correlation between rainfall and winter survival of bee colonies (Switanek et al., 2017) and honey harvest (Delgado et al., 2012) has been noted in the literature. Rainfall patterns are regularly observed by beekeepers for predicting flowering events. The juvenile period of bee forage species varies geographically and is also connected with variations in rainfall (Bradshaw et al., 2018; Burrows et al., 2008; Shedley et al., 2018). Terms such as "patchy flowering," "uneven production," and "consistently random flowering" were used by beekeepers to describe climate effects on the resource system. In addition, lack of nectar, thinning of nectar, and bitter nectar were reported and associated with climate change.

A relationship between rainfall patterns and flowering events (and nectar production) is evident with increasing use of inland forage sites (toward Coolgardie: Figure 7) to access good flowering events, i.e., a hive filled with honey within two weeks, resulting from increasingly variable precipitation. Rainfall shifts toward inland areas are supporting beekeepers with additional forage sites (RS5ai) but may lead to inequitable production (O1) because of fuel intensive, long-distance travel involved with accessing more remote locations. In addition, our SESF analysis has revealed impacts on other parts of the SES. For example, unpredictable flowering also escalates beekeepers' travel expenditure because of additional site visits to confirm resource availability prior to utilization (A4, A2b; Figure 11).

4.4.1.3 Burning of forage resources

Beekeepers understand fire in great detail, including frequency, intensity, and extent of disturbance. Forage species in the Mediterranean-type climates have naturally adapted to fires, however a species' response during the juvenile period—capacity of species to produce flowers and nectar—varies and depends on the frequency and intensity of burning (Bradshaw et al., 2018; Shedley et al. 2018). For instance, as cited in Bradshaw et al. (2018), Banksia sessilis takes 12–15 years postfire to reach maximum honey production, and frequent burns can result in loss of the species. In the SWAFR, almost 180,000 ha is burnt annually by DBCA to manage fuel load and avoid catastrophic fire events (Bradshaw et al., 2018). An association between burning and underutilization of sites is evident from beekeepers' statements such as "All our products go to smoke," "Parrot bush (*Banksia sessilis*) is completely lost to frequent burning at the coast," and "We use more private sites now government sites are not reliable - it's frequently burnt" (GS4,GS7).

Reducing harvesting levels or a complete loss of crop (nectar-bearing flowers) due to frequency, intensity, and timing (during budding season) of prescribed burns was noted as the main cause of conflict between beekeepers and government organizations (I4; Figure 11). We identified contradictory views regarding recovery of species after burning between government officials and beekeepers (RS6, RS10). This represents a critical gap between two knowledge systems and a challenge of integrating beekeepers' practical knowledge obtained through regular monitoring of flora with land management practices.

4.4.1.4 Understanding structural interconnectivities

Aligning management decisions to the complex, spatially explicit dynamics associated with human and ecological systems is vital in addressing sustainability issues and effective spatial planning in a SES (Leslie et al., 2015; Ovitz & Johnson, 2019). The multiscale, multidirectional applicability of our SESF provides opportunity to understand complex interconnectivities leading to these SES dynamics within the beekeeping industry. Understanding the structural interconnectivities of the beekeeping system through SESF mapping has revealed impacts on other parts of the SES that may not have been initially obvious. For example, a preference by beekeepers to access resources closer to their home location, i.e., close to urban and peri-urban areas to save the time and costs involved in hive-transportation, can lead to increased intensity of resource use and high competitiveness within close proximity to urban, peri-urban systems. Research findings indicate that migration decisions by beekeepers reflect self-organization within the beekeeping SES, with part-time beekeepers preferring to migrate hives within a couple of hundred kilometers from their home location, whereas full-time (mostly family) beekeepers are willing to migrate hives longer distances to access forage resources.

The importance of integrating local ecological knowledge with local management practices in SES is also highlighted in our research (Colding & Barthel, 2019; Hill et al., 2019; Maderson & Wynne-Jones, 2016; Uchiyama et al., 2017) through the identification of third and fourth tier variables aided by multigenerational beekeepers. Through considering the spatially explicit nature of social-ecological interactions, collective action involving local actors and the government may result in more effective spatial planning for the industry (Dressel et al., 2018; Leslie et al., 2015; Nagendra & Ostrom, 2014; Partelow, Glaser, et al., 2018). For instance, beekeepers' local knowledge can be used to adjust burning regimes and schedules to avoid burning flora during budding or nectar flow.

4.5. Conclusion

In this paper we have presented the first application of Ostrom's SESF to understand structural interconnectivities within the beekeeping industry. We combined various qualitative research methods to identify important social and ecological components of the bee-human system and their interconnectivities. We also identified and discussed key social-ecological pressures to the beekeeping industry, highlighting the need for integrated decision making and incorporation of local ecological knowledge in management decisions. As such, our SESF assessment can be used to facilitate multidirectional communication and knowledge exchange between beekeeping industry actors to address stakeholder needs, particularly for the improved management of common pooled resources. Additionally, the framework can be used to inform integrated policy design in order to sustain apiary production while safeguarding bee-diversity and associated ecosystem services. Although certain lower tier variables, e.g., apiary permits (GS8ai), proximity of resource units (RU3ai), and load size (RU5ai), are unavoidably specific to the WA system, the diagnosis presented here can guide sustainable management decision making associated with other bee-human systems including wild bee conservation and nonmigratory beekeeping, as well as migratory beekeeping in alternative geographical locations. For example, conflicts arising from competition over Manuka resources in New Zealand (Lloyd et al., 2017) could be managed using our SESF given the transferability of first and second tier variables across systems. Our recommendation is to build upon this foundational research to initiate a framework application to quantitatively investigate the outcomes of system interconnectivities (e.g., Dressel et al., 2018; Leslie et al., 2015; Pacilly et al., 2019) within the bee-human system. Such an approach would enable complex social-ecological systems modeling to test the implications of behavioral decision making, such as exploring how factors that govern landscape mobility affect beehive migration and impact system sustainability.

Chapter 5. Assessing impacts of climate change on the spatial distribution of key bee forage species in Western Australia using the MaxEnt species distribution model

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Parts of this chapter have been published in Data in Brief as Patel, V., B. Boruff, E. Biggs, and N. Pauli. 2023. Data representing climate-induced changes in the spatial distribution of key bee forage species for southwest Western Australia. Data in Brief. 46:108783 after the thesis examination was completed. The published version of this chapter is attached as Appendix 8.

5.1 Motivation

Access to quality forage resources for maintaining healthy and productive bee colonies is critical for successful beekeeping. A range of biophysical and legislative factors affect beekeepers' ability to access forage resources in the present, and the impact of future environmental change on forage species will further affect the spatial-temporal patterns of beehive migration and associated apiary production. Chapter 4 of this thesis illustrated the structural interconnectivities between forage resources and beehive mobility. To identify the spatial distribution of forage resources now and under future projected climate, this Chapter presents species distribution modelling (SDM) for the 30 most important melliferous flora species for honey production in Western Australia (WA) (as defined by beekeepers). The results from Chapter 5 were used within an integrated model (*B-Agent*) defining and operationalising beehive migration interactions, which is presented in Chapter 6 and includes a case study exploring the interconnectivities between forage-availability and beehive migration relative to a future climate in WA.

Chapter 6 is in revision with the journal *Applied Geography*; a much-abridged version of the work presented here in Chapter 5 was included within the Supplementary Material of that publication.

Here, we present an expanded version of the methods and results used to develop the species distribution model, as it reflects an important component of the overall research design. Chapter 5 addresses thesis objective 3, which focuses on identifying the change in the current geographic distribution of key bee forage species in Western Australia relative to climate change (one of the three priority pressures identified in Chapter 4). Specifically, this chapter addresses one research question: What is the spatial distribution of key bee forage species change under future projected climates?

5.2 Introduction

The Western Australian (WA) beekeeping industry relies on native flora for approximately 80% of honey production including numerous eucalypt species, a mix of understory plants and grasses (Arundel et al., 2016), as well as woodlands, heaths, and shrubs (Benecke, 2007). WA's honey producing landscapes are restricted to the southwest corner of the state (Benecke, 2007), which is one of the original 25 global biodiversity hotspots as defined by Myers et al. (2000). The region is home to a great diversity of plant species, including a high diversity in the plant families of Myrtaceae, Proteaceae, and Ericaceae (Beard et al., 2000), which comprise some of the most important families of bee forage species targeted in WA (Smith, 1969). Since the 1970s, the southwest region of WA has experienced a 10-20% reduction in rainfall (Hughes, 2011; Makuei et al., 2013), particularly in winter rainfall (Andrys et al., 2017). Reduction in precipitation coupled with increasing temperature has manifested in increased drought frequency (Andrys et al., 2017; Makuei et al., 2013), which impacts numerous plant species resulting in alterations to their geographic distribution (Fitzpatrick et al., 2008; Hamer et al., 2015; Yates et al., 2010). This shift in species ranges has the potential to alter the spatial distribution of ecosystem service provisioning (e.g., provisioning of food and livelihood) offered by individual species (Mastrantonis et al., 2019).

The geographic distribution of a species is directly linked to environmental suitability and the availability of biophysical resources required for a species to survive. Understanding the geographic distribution of a species is critical in light of recent global environmental change (IPCC, 2022). Species distribution modelling (SDM) is widely used to predict geographic ranges based on a statistical relationship between species occurrence and environmental conditions (Elith et al., 2011). The statistical relationship underlying SDMs can predict future distribution ranges if projected environmental conditions are used. Such estimations are important not only for informing conservation efforts for the species itself, but also for assessing the effects on related ecosystems. For example, understanding the dynamics of spatiotemporal variation in forage resource availability and species movement informs sustainable rangeland management strategies (Fust & Schlecht, 2018). However, despite the critical role of forage (nectar and pollen sources) availability and diversity for optimum apiary site selection (Camargo et al., 2014; Galbraith et al., 2017; Pantoja et al., 2017; Pilati & Prestamburgo, 2016; Sarı et al., 2020; Zoccali et al., 2017), limited research has examined how a shift in the spatial distribution of individual forage species will impact beekeeping sustainability.

5.2.1 Overview of Species Distribution Modelling (SDM) approaches

Ecosystems are home to a wide variety of species, each of which are adapted to survive and thrive under a particular set of environmental conditions. Over the past two decades, a large number of SDM approaches have been used to (i) Understand the causal relationship between species and the environment, (ii) Map the distribution of species within the same time period, and (iii) Project the distribution to relevant spatial and temporal settings (Araújo et al., 2019). Early SDM approaches focused on simply identifying the geographic envelope of a matched environment by equally weighting each predictor variable, which later, evolved into more advanced regression methods and machine-learning models that account for complex non-linear responses of species to environmental conditions (Elith & Leathwick, 2009).

SDM approaches have been categorised as presence-absence and presence-only (often called as presence-background) approaches. Presence-absence approaches (e.g., Generalised Linear Models) train models using species presence and absence information known, *a priori*, to the modeller (e.g., collected from field surveys), whereas presence-only (e.g., Maximum Entropy) approaches rely on species presence data that reflects a collection of known occurrences and may be compiled from multiple sources e.g., Atlas data (Elith & Graham, 2009). In presence-only modelling approaches, the model predicts a species distribution using species occurrence locations (used to characterize the environment where species is known to occur) and a set of background points that are randomly distributed across the area (used to characterize the environment within the whole study area).

The performance of an SDM algorithm depends on an individual species' environmental settings (Qiao et al., 2015), spatial extent of the study region (Anderson & Raza, 2010), spatial resolution of input data (Manzoor et al., 2018), choice of predictor variables, and the climate scenario being modelled (Porfirio et al., 2014). Therefore, it is important to select an SDM algorithm based on the specific requirements of each distribution modelling application (Guillera-Arroita et al., 2015). SDMs are an increasingly popular tool for informing conservation and restoration initiatives (Domisch et al., 2019; Zellmer et al., 2019), particularly for assessing the impacts of climate change on species distribution (Pecchi et al., 2020; Zhao et al., 2021). In addition, the SDM outputs assist researchers with critical insights into expected future changes in resource distributions, which can be integrated with other modelling and simulation methodologies to assist in managing the effects of climate change on social-ecological systems (Miller & Morisette, 2014).

5.2.2 Maxent modelling

Maxent is a machine learning SDM algorithm based on the maximum entropy principle, which combines presence-only data and randomly selected background points with environmental predictors to estimate a probability distribution that is spread and uniform (Elith et al., 2011;

Phillips, Anderson, et al., 2006). Maxent is an easy-to-use presence-only method with comprehensive support documentation and high prediction performance when compared to other known methods (Elith et al., 2006; Elith et al., 2011). Since its introduction in 2004, Maxent has been included in various machine learning software packages e.g., Python, R etc. The algorithm is also available as a more user-friendly interface as the *MaxEnt* software (Phillips, Dudik, et al., 2006).

While Maxent is a widely used and popular species distribution modelling tool, it has also received some criticism in the scientific literature. Critiques include concerns about (i) overfitting, particularly when using small sample sizes or large number of environmental variables (Merow et al., 2013); (ii) reliance on environmental variables, which can limit its applicability to situations where environmental data is available; and (iii) the potential for biased results, particularly when using biased or incomplete sampling data (Guisan & Rahbek, 2011). However, recent studies have shown that Maxent's performance can be improved by careful selection of environmental variables and regularization techniques (Fourcade et al., 2014; Fithian et al., 2015).

Despite these criticisms, Maxent remains the most widely used species distribution model due to its high accuracy, flexibility, and accessibility. Maxent has been adopted by government and non-government organisations the world over for large-scale biodiversity mapping projects such as the Atlas of Living Australia (http://www.ala.org.au/) (Elith et al., 2011). Maxent has been widely used in managing climate change impacts on forests (Booth, 2018), and to assess the impact of climate change on the geographic distribution of tree species (Gonzalez-Orozco et al., 2016; Zhang et al., 2022), rendering it the preferred SDM approach for this research. With this overview, the presence-only Maxent algorithm was selected to assess the change in geographic distribution of 30 bee forage species relative to a changing climate.

5.3 Methods

5.3.1 Predicting the geographic distribution of target forage species

Thirty bee forage species targeted by beekeepers were shortlisted using stakeholder engagement methods outlined in Section 6.2.2. Stakeholder engagement with beekeepers led to the development of a list of 30 high-priority bee forage species (full methods are provided in Chapter 6, section 6.2.2.1). The 30 species targeted by WA apiarists include 23 species from the Myrtaceae family (21 *Eucalyptus* spp., and one species each of *Corymbia* and *Calothamnus*), five Proteaceae species (4 *Banksia* spp., one *Hakea* sp.), and two species from the Ericaceae (two species of *Leucopogon*). These species are discussed as coastal eucalypt, inland eucalypt and non-eucalypt bee forage species in the remainder of this chapter (Table 5). *MaxEnt* software (version 3.4.1; Phillips, Dudik, et al. (2006)) was used to model the geographic distribution of each target species under current and future climate scenarios.

5.3.1.1 Species presence data

Species presence data for the 30 study species were downloaded using the spatial portal Atlas of Living Australia (https://spatial.ala.org.au). These data were further cleaned by removing samples with high coordinate uncertainty (>1 km) to ensure accuracy of species presence. Additional species presence samples were acquired as primary species targeted at each apiary permit location in WA through Participatory GIS mapping with commercial beekeepers. Occurrence data was combined to overcome spatial bias in ALA records (Fithian et al., 2015; James et al., 2018). This resulted in a total of 12,623 presence data points for 30 study species with which to build SDMs.

5.3.1.2 Environmental variables and climate scenario

Environmental data used in this study includes 19 bioclimatic variables prepared using the Australia current climate (1976 – 2005) dataset (http://www.bom.gov.au/jsp/awap/) at 1 km spatial resolution. The future scenario represents a moderate emission Representative Concentration Pathway (RCP)

6.0 scenario for the Global Climate Model (GCM) CSIRO Mk3 for 2055, using a bioclimate dataset prepared for Australia across the time period (2015 – 2085) (Vanderwal, 2012). Here, projections for 2055 were used to understand the change in bee forage availability in the relatively near future, in order to identify the climate change impacts on the rapidly growing beekeeping industry in WA.

Although predictor collinearity is automatically accounted for within Maxent (Elith et al., 2011; Feng et al., 2019), more accurate results can be obtained using a smaller subset of biophysical predictor variables rather than a full suite of 19 bioclimatic variables (Low et al., 2021). Therefore, a subset of predictor variables was preselected using a Pearson correlation test and biological relevance highlighted in previous SDM studies of multiple eucalypt (Butt et al., 2013; Gonzalez-Orozco et al., 2016; Hamer et al., 2015) and *Banksia* species (Fitzpatrick et al., 2008; Yates et al., 2010). Table 4 provides a list of 19 bioclimatic predictors with the selected variables in bold.

Maxent uses a range of mathematical functions to represent nonlinear complexities in the relationships between predictor variables and species distributions (Low et al., 2021). Six primary feature functions are used in Maxent including linear, product (product of two variables), quadratic (square of variables), threshold (a "step" function generating different constant function above a threshold; alike piecewise constant spline), hinge (similar to threshold but generates a linear function above the threshold; a like piecewise linear spline), and categorical (Elith et al., 2011). Models constructed solely with the hinge function produce complex but smooth response curves (Elith et al., 2011), which may improve model performance and more closely represent the species' fundamental niche (Phillips & Dudík, 2008). Therefore, drawing upon the work of Gonzalez-Orozco et al. (2016), only hinge features were used in this study to reduce complexity and improve model performance.

Table 4: List of bioclimatic variables used in species distribution modelling (SDM) using MaxEnt software. The variables with bold letters were selected for use in MaxEnt software to overcome collinearity in variables.

Code	Variable
Bio1	Mean annual temperature
Bio2	Mean diurnal range
Bio3	**Isothermality**
Bio4	Temperature seasonality
Bio5	**Max temperature of warmest month**
Bio6	Min temperature of coldest month
Bio7	Temperature annual range
Bio8	Mean temperature of wettest quarter
Bio9	Mean temperature of driest quarter
Bio10	Mean temperature of warmest quarter
Bio11	**Mean temperature of coldest quarter**
Bio12	**Annual precipitation**
Bio13	Precipitation of wettest month
Bio14	Precipitation of driest month
Bio15	Precipitation seasonality
Bio16	**Precipitation of wettest quarter**
Bio17	**Precipitation of driest quarter**
Bio18	Precipitation of warmest quarter
Bio19	Precipitation of coldest quarter

Species range change analysis was carried out by converting logistic outputs to binary presence absence grids using maximum training sensitivity plus specificity threshold (Liu et al., 2005). This threshold maximizes the sensitivity and specificity of the model and prevents overestimation of suitable habitats by reducing false positives (Loiselle et al., 2003) and has been used in the literature for modelling the distribution of species included in this research. The average output of five-fold cross-validation was selected for each species to assess the change in geographic distribution ranges between baseline and future. Detailed methods for determining species range change are provided in the next section (section 5.3.2). Threshold independent area under the curve (AUC) statistics were used for evaluating the predictive performance of SDMs, where an AUC of 0.5 indicates a null model (i.e., no differentiation between true and false positives); less than 0.5 indicates a model performing worse than random; 0.5 – 0.7 indicates a poor performance; 0.7 – 0.9 a moderate performance; and > 0.9 suggest high performance (Peterson et al., 2011).

5.3.2 Assessing the change in species geographic distribution ranges

Maxent outputs were converted from ASCII to Tiff file format using open source Geographic Information System software QGIS (version 3.10, https://www.qgis.org) for further analysis. To quantify the change in species range between baseline and future scenario, change in area and the direction of shift were calculated using QGIS. A complete GIS workflow is provided in Figure 12.

First, both baseline and future outputs for each species were reprojected to WGS 84/UTM Zone 50 S to facilitate area level calculations. The raster cell size was set at 3000m × 3000 m. The cell size was selected to represent WA's 3 km apiary separation regulation as discussed in Section 4.3.1.1. Reprojected raster layers were then converted to a binary presence-absence raster using maximum training sensitivity plus specificity logistic threshold (Gonzalez-Orozco et al., 2016; Hamer et al., 2015; Liu et al., 2005). Using the threshold values in Table 5, each species output was reclassified where pixel values less than the determined threshold were 0, and pixel values greater than the threshold were 1 (for baseline scenario) or 2 (for future scenario). The spatial overlap between baseline and future scenario for each species was calculated as the mathematical addition of the reclassified grids. The total number of presence pixels for each class including 'baseline only' (pixel value = 1), 'future only' (pixel value = 2), and 'baseline and future' (pixel value = 3) were then multiplied by the cell size (9 km^2) to calculate species distribution areas by class (Figure 12).

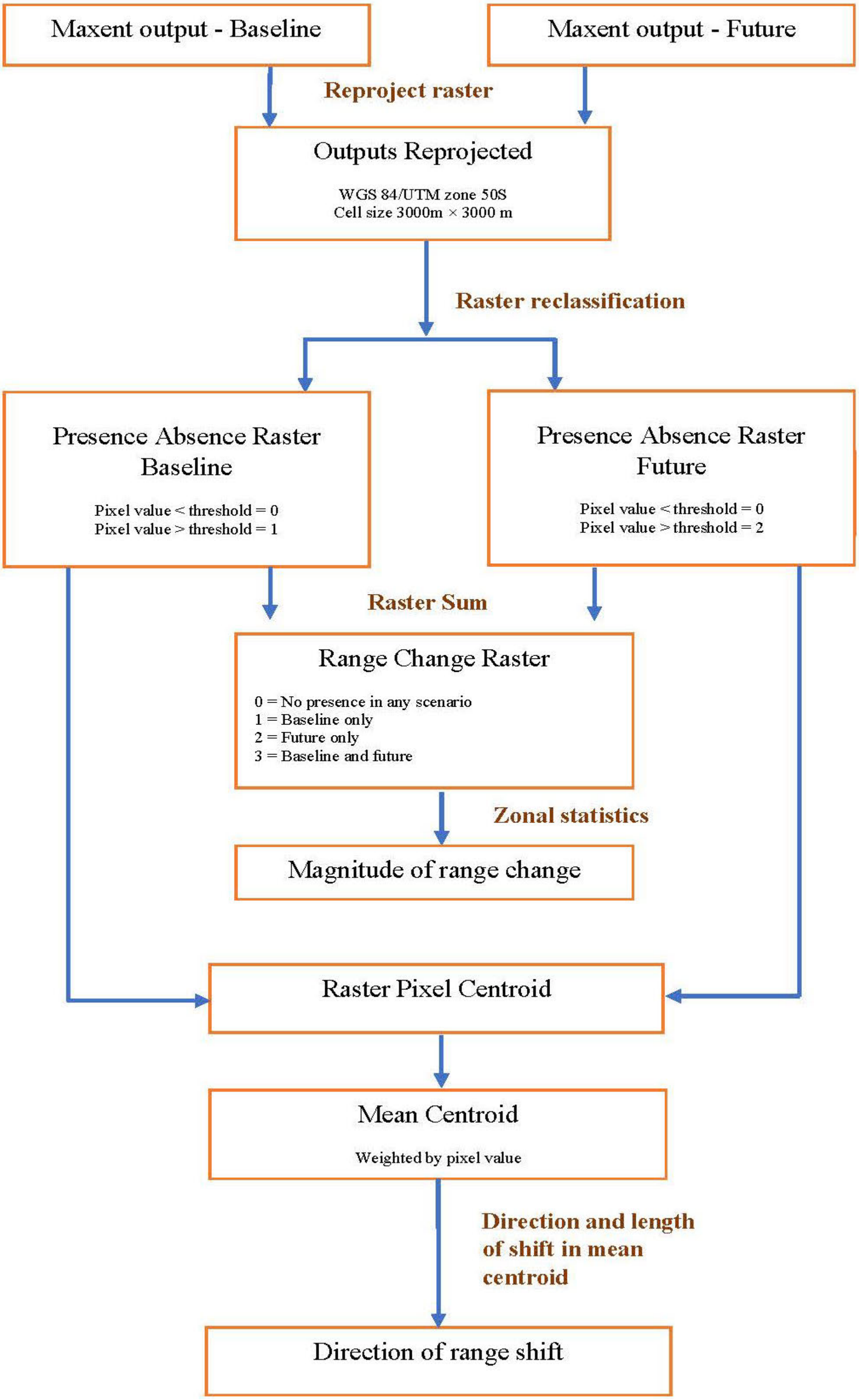


Figure 12: Workflow highlighting steps for range change analysis using QGIS

The percentage change in area of each species geographic range in the future was calculated as:

$$[(R_F/R_B) - 1] *100.$$

Where R_F represents the distribution area in the future (sum of area of pixel values 2 and 3) and R_B is the distribution area at baseline (sum of area of pixel values 1 and 3).

To assess the shift in distributions, the mean center (latitude and longitude) of presence cells for each species was calculated for the baseline and future scenario. The distance and compass directional shift between mean centers for each scenario was then calculated and together, the two metrics provided an indication of the magnitude and direction of changes to each species distribution following climate change. Results were then compared with previous studies reporting the distribution of multiple eucalypt (Booth, 2017; Butt et al., 2013; Gonzalez-Orozco et al., 2016; Hamer et al., 2015; Hughes et al., 1996) and *Banksia* species (Yates et al., 2010) in Australia under a moderate emissions climate scenario.

5.4 Results

5.4.1 Model predictive performance

The predicted SDMs obtained using the MaxEnt software showed moderate to high performance as measured using the AUC curve. The mean AUC was 0.93, with the test AUC ranging from 0.78 to 0.99 across all study species, indicating that the obtained geographic distributions of study species were described by environmental variables with high accuracy. The evaluation statistics and threshold value used to generate the binary presence-absence rasters are shown in Table 5.

Table 5: Mean AUC values for thirty forage species targeted by beekeepers in Western Australia derived from fivefold Maxent modelling. The threshold represents maximum training sensitivity plus specificity logistic threshold used to convert Maxent outputs into a presence-absence raster for each species. Classification of species is based on the geographic distribution observed in this research. This table (except the column 'Classification') is included as Table 5.4 in Appendix 5.

Target species	Classification	Threshold	Training AUC	Test AUC
Banksia attenuata	Non-eucalypt	0.13	0.96	0.95
Banksia menziesii	Non-eucalypt	0.03	0.99	0.99
Banksia sessilis	Non-eucalypt	0.20	0.95	0.93
Banksia sphaerocarpa	Non-eucalypt	0.25	0.94	0.90
Calothamnus quadrifidus	Costal eucalypt	0.36	0.88	0.87
Corymbia calophylla	Costal eucalypt	0.18	0.93	0.93
Eucalyptus accedens	Costal eucalypt	0.15	0.97	0.97
Eucalyptus annulata	Costal eucalypt	0.28	0.96	0.94
Eucalyptus burracoppinensis	Inland eucalypt	0.25	0.96	0.92
Eucalyptus cornuta	Costal eucalypt	0.15	0.98	0.98
Eucalyptus diversicolor	Costal eucalypt	0.16	0.99	0.99
Eucalyptus dundasii	Inland eucalypt	0.18	0.99	0.98
Eucalyptus flocktoniae	Inland eucalypt	0.31	0.87	0.90
Eucalyptus incrassata	Costal eucalypt	0.29	0.91	0.87
Eucalyptus lesouefii	Inland eucalypt	0.21	0.98	0.98
Eucalyptus longicornis	Inland eucalypt	0.40	0.86	0.88
Eucalyptus loxophleba	Costal eucalypt	0.40	0.80	0.78
Eucalyptus marginata	Costal eucalypt	0.15	0.94	0.93
Eucalyptus melanoxylon	Inland eucalypt	0.32	0.92	0.90
Eucalyptus occidentalis	Costal eucalypt	0.23	0.94	0.91
Eucalyptus platypus	Costal eucalypt	0.27	0.97	0.94
Eucalyptus ravida	Inland eucalypt	0.29	0.95	0.96
Eucalyptus redunca	Costal eucalypt	0.16	0.96	0.93
Eucalyptus salubris	Inland eucalypt	0.31	0.87	0.86
Eucalyptus stricklandii	Inland eucalypt	0.31	0.99	0.98
Eucalyptus transcontinentalis	Inland eucalypt	0.25	0.93	0.90
Eucalyptus wandoo	Costal eucalypt	0.18	0.93	0.93
Hakea trifurcata	Non-eucalypt	0.22	0.93	0.91
Leucopogon conostephioides	Non-eucalypt	0.21	0.93	0.93
Leucopogon oldfieldii	Non-eucalypt	0.17	0.99	0.99

Precipitation of the wettest quarter (Bio16) was the key predictor variable with a Permutation Importance (PI) score of greater than 10% for 23 of the 30 study species. A significant difference in the important predictors was observed between coastal and inland eucalyptus species (identified in Table 5). Annual precipitation (Bio12), which is a key predictor for 10 out of 13 coastal eucalypt species, has a high PI score for only two out of 10 inland eucalypt species. Similarly, Isothermality

(Bio3) and Precipitation of driest quarter (Bio17) received high PI scores for eight and six of the 10 inland eucalypt species, respectively, but was only found to be an important predictor for four coastal eucalypts. Mean temperature of coldest quarter (Bio11) remained insignificant with PI < 10% for all eucalypts, except *Calothamnus quadrifidus*.

For non-eucalypt bee forage species (identified in Table 5), Annual precipitation (Bio12) remained the most important predictor with a PI score > 10% for six out of seven non-eucalypt forage species. Interestingly, while insignificant for eucalypt species, mean temperature of the coldest quarter (Bio11) was one of the most important predictors (with PI score > 10%) for 5 out of 7 non-eucalypt species. Similarly, Isothermality (Bio3) was found to be insignificant in predicting the distribution of non-eucalypt forage species, despite having a high PI for 12 of the total 23 eucalypts examined in the study. Permutation importance (%) of predictor variables are provided in Figure 13.

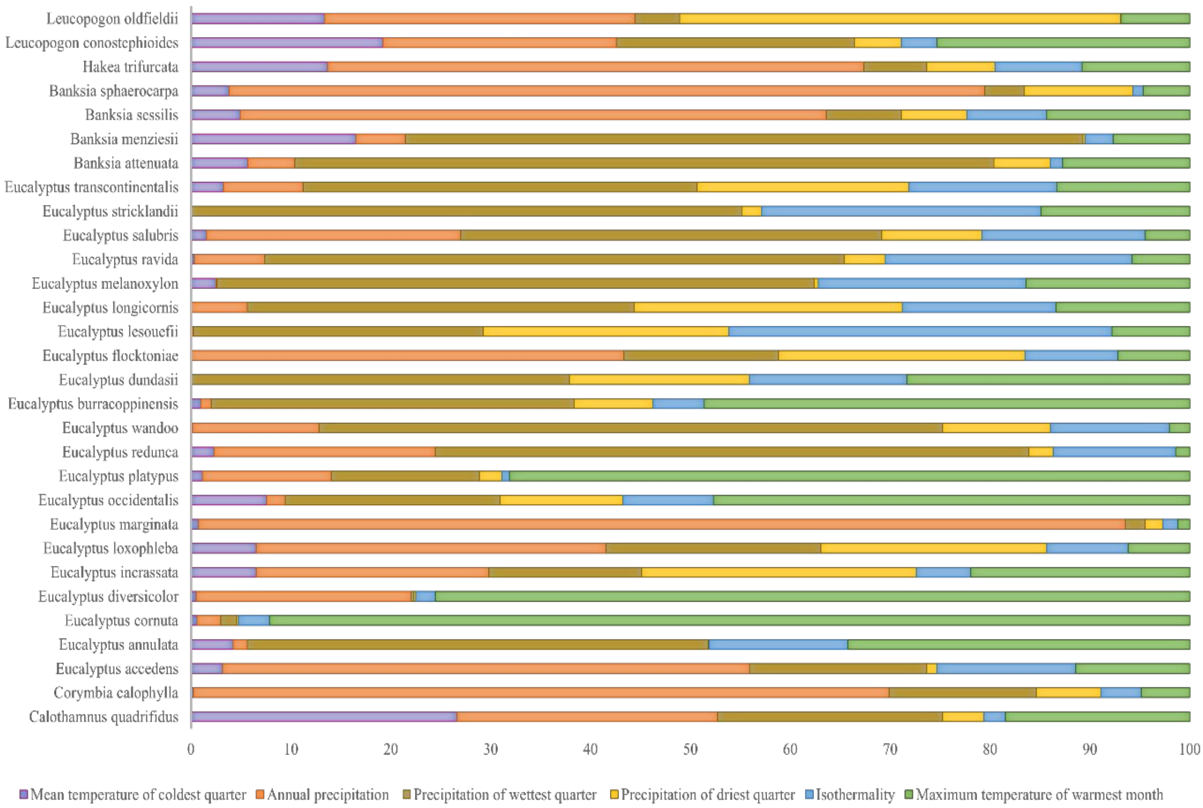
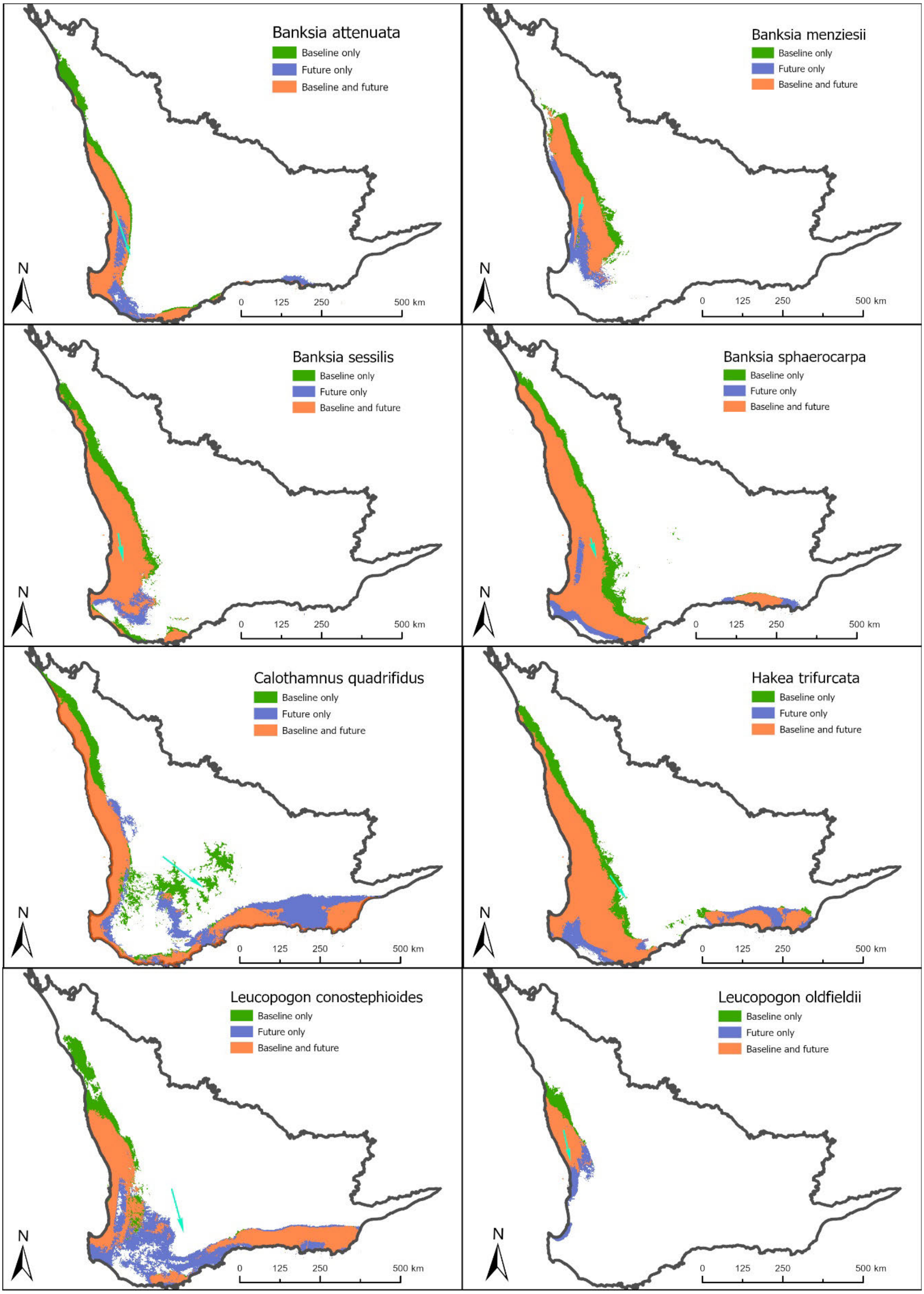


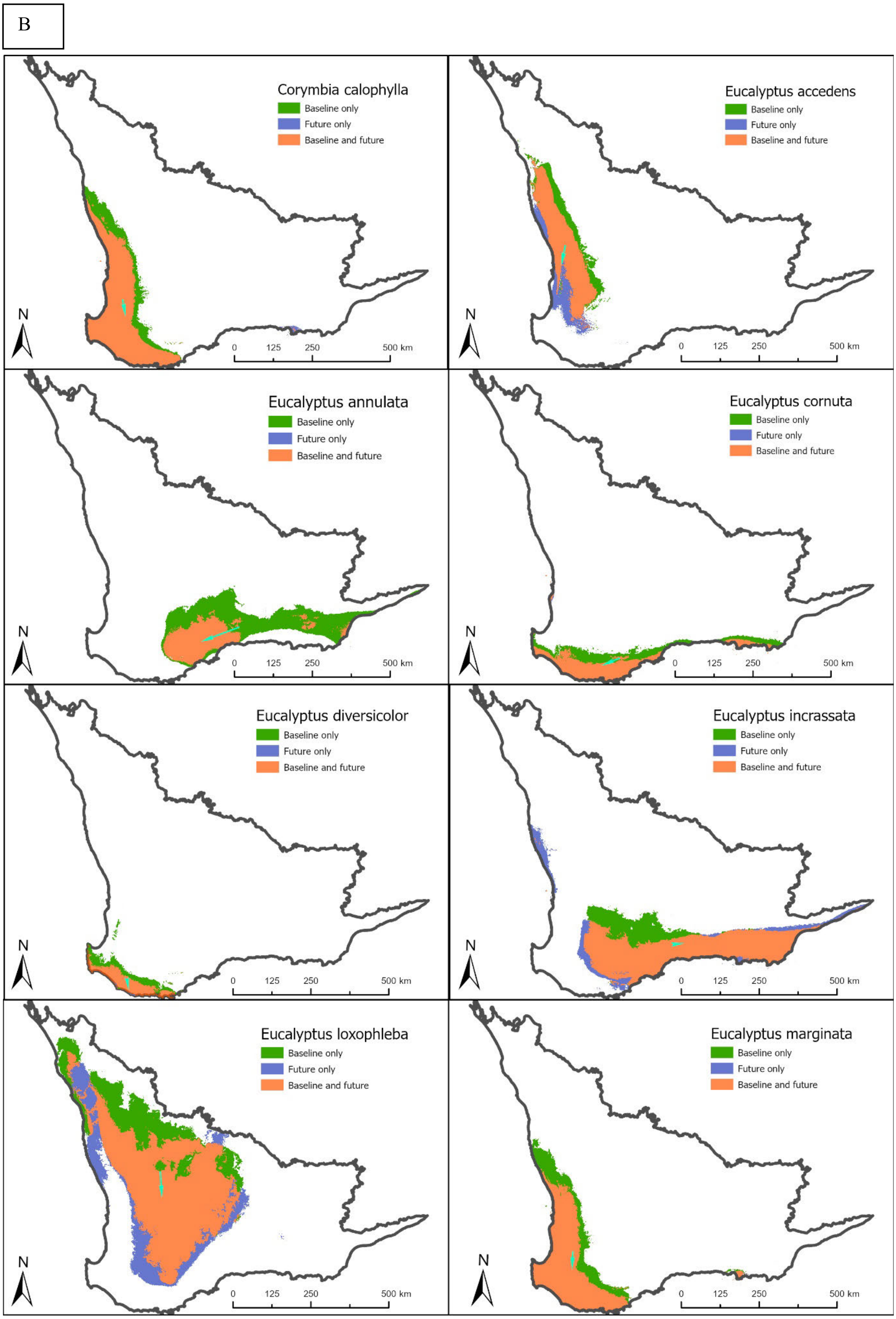
Figure 13: Permutation Importance (%) contribution of predictor variables for each study species

5.4.2 Change in geographic distribution of key bee forage species

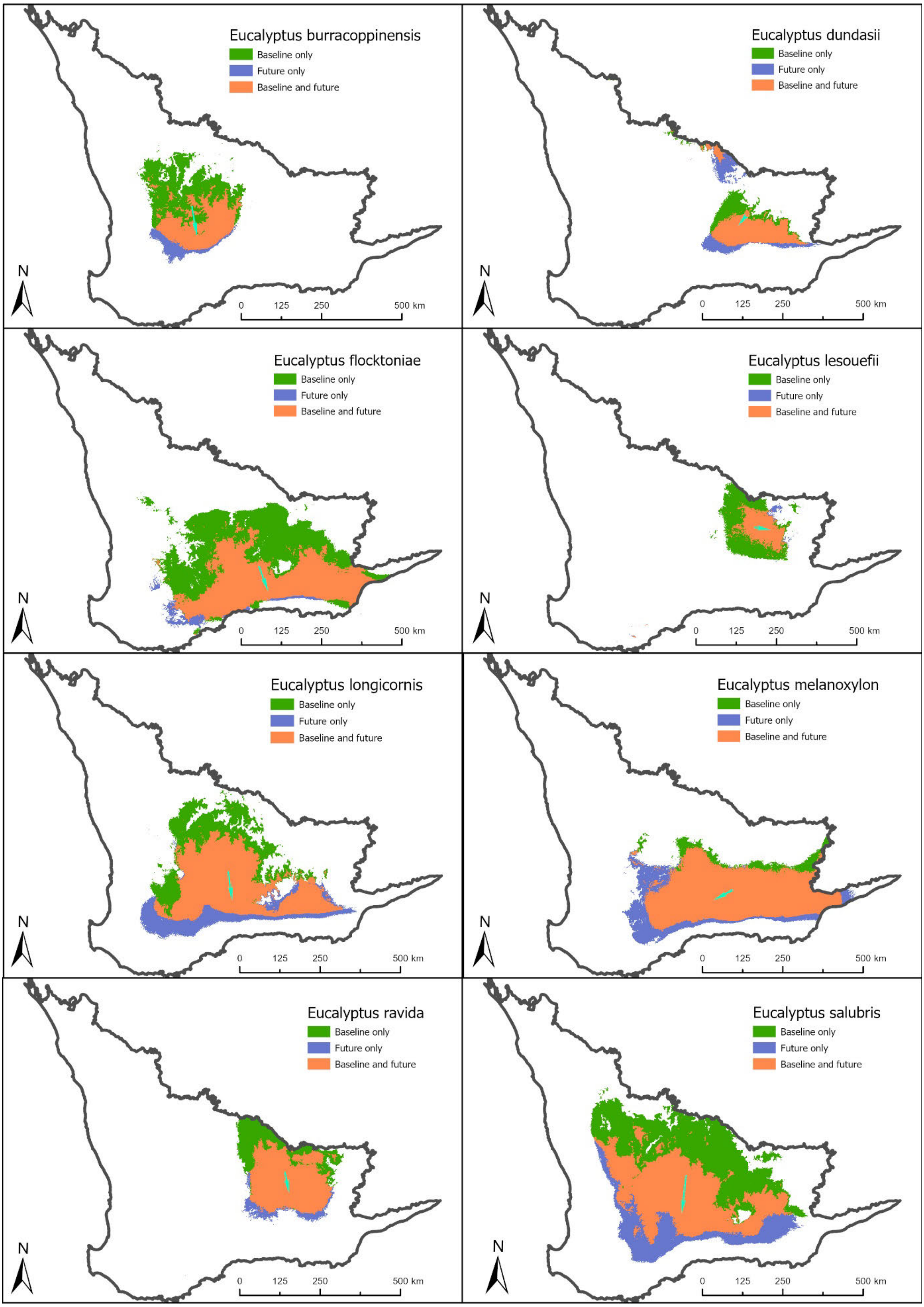
Individual species SDM results suggest that the geographic range of 23 study species will contract by an average of 30%. A poleward shift is evident in predicted distributions with a southward shift in 13; a southeast shift in 9, a southwest shift in 4, and an eastward shift in 4 of the study species. Among non-eucalypt forage species, *Leucopogon conostephioides* (35.9 %) and *Leucopogon oldfieldii* (12.2 %) exhibit range expansion, whereas the remaining five species, including four Banksia species showed contracting geographic distributions, with the highest loss (16.7 %) observed in *Banksia sessilis*. The distribution of individual species for both baseline and future scenarios presented here, as well as directional shifts are highlighted in Figure 14 (A-D).

A


Banksia attenuata
Baseline only
Future only
Baseline and future
N
0 125 250 500 km
Banksia menziesii
Baseline only
Future only
Baseline and future
N
0 125 250 500 km
Banksia sessilis
Baseline only
Future only
Baseline and future
N
0 125 250 500 km
Banksia sphaerocarpa
Baseline only
Future only
Baseline and future
N
0 125 250 500 km
Calothamnus quadrifidus
Baseline only
Future only
Baseline and future
N
0 125 250 500 km
Hakea trifurcata
Baseline only
Future only
Baseline and future
N
0 125 250 500 km
Leucopogon conostephioides
Baseline only
Future only
Baseline and future
N
0 125 250 500 km
Leucopogon oldfieldii
Baseline only
Future only
Baseline and future
N
0 125 250 500 km


B
Corymbia calophylla
Baseline only
Future only
Baseline and future
Eucalyptus accedens
Baseline only
Future only
Baseline and future
Eucalyptus annulata
Baseline only
Future only
Baseline and future
Eucalyptus cornuta
Baseline only
Future only
Baseline and future
Eucalyptus diversicolor
Baseline only
Future only
Baseline and future
Eucalyptus incrassata
Baseline only
Future only
Baseline and future
Eucalyptus loxophleba
Baseline only
Future only
Baseline and future
Eucalyptus marginata
Baseline only
Future only
Baseline and future
N
0 125 250 500 km

C


Eucalyptus burracoppinensis
Baseline only
Future only
Baseline and future
Eucalyptus dundasii
Baseline only
Future only
Baseline and future
Eucalyptus flocktoniae
Baseline only
Future only
Baseline and future
Eucalyptus lesouefii
Baseline only
Future only
Baseline and future
Eucalyptus longicornis
Baseline only
Future only
Baseline and future
Eucalyptus melanoxylon
Baseline only
Future only
Baseline and future
Eucalyptus ravida
Baseline only
Future only
Baseline and future
Eucalyptus salubris
Baseline only
Future only
Baseline and future
N
0 125 250 500 km

D

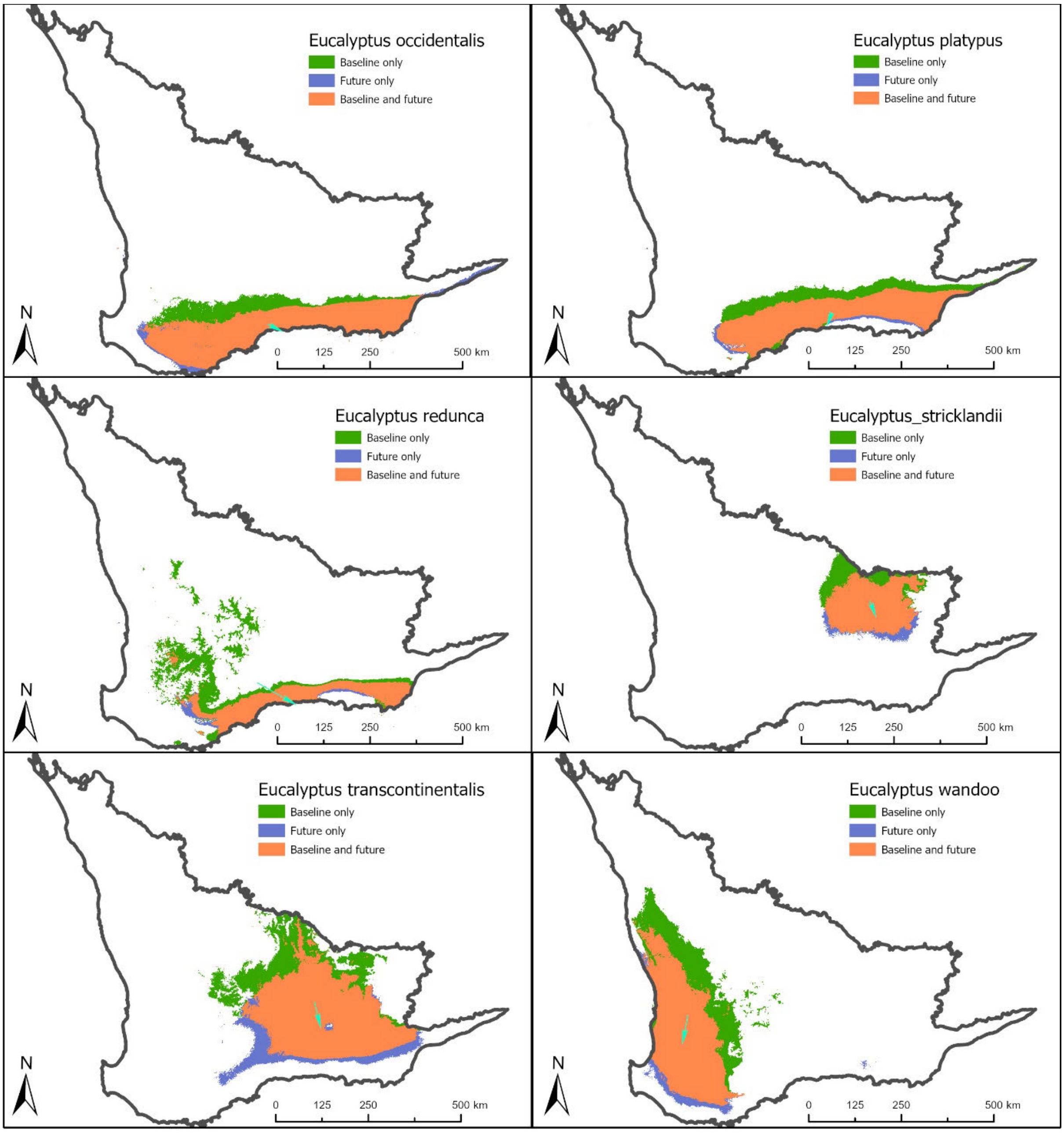


Figure 14: Change in the geographic distribution of important bee forage species in WA relative to a future climate scenario (2055). Pixels in green represent species presence in only the baseline scenario, blue colour represents presence in only future scenario, and orange represents availability of species in both baseline and future scenario. Arrows represent the shift in the spatial distribution range of each species, where the length of the arrow is proportionate to the distance of shift.

5.5 Discussion

5.5.1 Species projected distributions

Research presented in this chapter has demonstrated the change in spatial distribution of thirty bee forage species relative to future climate change. For majority of the study species, their current geographic range was identified as shifting southward. At a global scale, a poleward shift in species due to climate change is highlighted with high confidence in a recent IPCC report (IPCC, 2022). For the 30 study species, similar reductions in distributions as well as lateral and poleward shifts in ranges have been highlighted in similar analyses (Butt et al., 2013; Gonzalez-Orozco et al., 2016; Hamer et al., 2015; Yates et al., 2010). A detailed comparison between the results produced in this study and those found within the literature are presented in Table 6.

The results of magnitude and directional shift of ranges were compared with Gonzalez-Orozco et al. (2016), in which the results of similar analysis is presented at individual species level for 21 of the 23 eucalypt species modelled in this Chapter. Ten species show the same southward directional shift; for seven species, the shift differs slightly (i.e., the next cardinal direction), while four species show large differences in the directional shift when compared with Gonzalez-Orozco et al. (2016). Although not as detailed, findings presented by Fitzpatrick et al. (2008) and Yates et al. (2010) support the SDM results presented here for four banksias (*Banksia attenuata, B. menziesii, B. sessilis* and *B. spherocarpa*), i.e., a reduction of up to 80% in geographic distribution, of four banksia study species (Fitzpatrick et al., 2008), and suggesting a strong south and westward shift for sixteen species, including *B. attenuata* and *B. menziesii* (Yates et al., 2010).

Table 6: Summary table of % change in species spatial distribution, type, magnitude and direction of range shift for 30 key bee forage species targeted by beekeepers in WA. The shift direction was calculated as 45 degree intervals using code applied in QGIS with the break values 348.75 - 33.75 as North; 33.75 -78.75 as Northeast; 78.75-123.75 as East; 123.75 – 168.75 as Southeast; 168.75 - 213.75 as South; 213.75 - 258.75 as Southwest; 258.75 - 303.75 as West and 303.75 - 348.75 = Northwest.

Target species	**Results of this research**			**Results reported in the SDM literature**			
	Change [%]	**Shift [km]**	**Direction**	**Change [%]**	**Shift [km]**	**Direction**	**Source ‡**
Banksia attenuata	-0.5	133.8	SE	-80 – 0	NA	NA	C
Banksia menziesii	-2.1	124.4	S	-30 – 0	NA	NA	C
Banksia sessilis	-16.7	65.5	S	-50 – 0	NA	NA	C
Banksia sphaerocarpa	-9.5	41.6	SE	-110 – 0	NA	NA	C
Calothamnus quadrifidus	8.2	135.6	SE	NA	NA	NA	D
Corymbia calophylla	-21.5	34.2	S	-41.6	64	S	A
Eucalyptus accedens	1.0	44.7	S	-34	70	W	A, B
Eucalyptus annulata	-63.6	110.3	SW	-54.9	83	S	A
Eucalyptus burracoppinensis	-46.9	71.8	S	-43.8	152	S	A
Eucalyptus cornuta	-41.0	42.1	SW	-58	65	S	A
Eucalyptus diversicolor	-40.4	16.0	S	-65.3	28	S	A, B
Eucalyptus dundasii	0.7	4.9	SW	-71.3	173	SE	A
Eucalyptus flocktoniae	-47.7	62.3	SE	-39.9	113	S	A
Eucalyptus incrassata	-6.1	10.9	E	-7.2	57	SW	A, B
Eucalyptus lesouefii	-59.0	30.0	E	6.8	19	S	A
Eucalyptus longicornis	-13.4	69.0	S	-21.2	89	S	A, B
Eucalyptus loxophleba	-4.3	63.2	S	-28.3	116	S	A
Eucalyptus marginata	-26.9	37.8	S	-45.9	74	S	A, B
Eucalyptus melanoxylon	14.2	44.8	SW	-2.8	43	SE	A
Eucalyptus occidentalis	-18.8	25.9	E	-48.2	64	S	A
Eucalyptus platypus	-24.2	18.5	S	NA	NA	NA	NA
Eucalyptus ravida	-21.9	44.6	S	-66.7	177	S	A
Eucalyptus redunca	-47.8	101.5	E	-49.6	110	S	A
Eucalyptus salubris	-25.8	97.1	S	-15.3	97	S	A, B
Eucalyptus stricklandii	-16.1	28.0	SE	-70.3	207	S	A
Eucalyptus transcontinentalis	-13.1	55.1	SE	-42.8	119	S	A
Eucalyptus wandoo	-28.3	60.5	S	-48.3	93	S	A, B
Hakea trifurcata	-4.8	69.7	SE	NA	NA	NA	NA
Leucopogon conostephioides	35.9	119.2	SE	NA	NA	NA	NA
Leucopogon oldfieldii	12.2	80.1	SE	NA	NA	NA	NA

‡ Letters corresponds to the sources listed below.

A - Gonzalez-Orozco et al. (2016); B - Hamer et al. (2015); C - Fitzpatrick et al. (2008); D - Nistelberger et al. (2014); NA - No comparable information found in literature

Contrasting results were also observed, particularly for some inland species, for example, significant range loss (59%) was identified in *Eucalyptus lesouefii* whereas Gonzalez-Orozco et al. (2016) reported an expansion of 6.8%. These contrasting results could be due to differences in the spatial extent of the study regions (Anderson & Raza, 2010), spatial resolution (Manzoor et al., 2018), choice of predictor variables and climate scenarios (Porfirio et al., 2014). The variable selection in Gonzalez-Orozco et al. (2016) has been criticised by Booth (2017) who conducted the same research on a subset of Gonzalez's species and found probable overestimations in their results. Furthermore, here a larger reduction in the distribution of coastal eucalypt species was observed when compared to inland species, which is contrary to Hamer et al. (2015). However, this discrepancy could be due to the generalisation of results based on a different group of species, as Hamer et al. (2015) only includes two of the ten inland species and four of the thirteen coastal species included in this research.

5.5.2 Implications to ecological and social systems

This research presents a novel application of a multispecies SDM approach focusing on understanding the change in key bee forage species in WA. Despite some contrasting results, the SDM outputs produced in this research provides insights into the potential impacts of climate change on important bee forage species in WA. The study species include dominant tree and shrub species from a variety of habitat types, and changes in these species are likely to have repercussions to the ecological and social systems where facilitatory relationship exists. The infinite dispersal of species is a commonly used assumption in SDMs assessing climate change impacts on individual species, which assumes the presence of species at the future spatial extent of environmental suitability for individual species (Yates et al., 2010).

If the future availability of species mirrors the availability of a suitable environment, a contraction in species range could reflect a decline in other symbiotically or ecologically linked species as well.

Such indirect effects of climate change have been highlighted in recent research, in which the availability of primary food source was found as a primary driver of variation in breeding frequency in forest red-tailed black cockatoos (*Calyptorhynchus banksia naso*) in WA (Mastrantonis et al., 2019). However, evaluating how changing species distributions can affect the livelihoods of individuals who rely on these species is a relatively less explored interdependence. Integrating SDMs into social-ecological system models through scenario planning provides an opportunity to understand such interdependent relationships (Miller & Morisette, 2014).

5.5.3 Towards integrating SDMs into *B-Agent*

The *B-Agent* modelling approach presented in the following chapter (Chapter 6) integrates the SDM outputs of the thirty bee forage species presented here in order to develop scenarios representing baseline and future forage-availability environments for incorporation into the hive migration decision-making agent-based model. Here, the term ‘forage-availability’ represents (i) the number of flowering bee forage species (out of a total maximum of 30 priority species) and (ii) flowering of two premium bee forage species (*Eucalyptus marginata* and *Corymbia calophylla*). Each forage-availability scenario includes a set of 24 grids (two grids per month), created using a stacked SDM approach (S-SDM). A S-SDM approach involves first independently predicting the distribution of each species and then stacking them to predict species richness and composition (Guisan & Rahbek, 2011). A S-SDM approach has been used in predicting plant species richness (Dubuis et al., 2011; Lu et al., 2021; Macedo-Santana et al., 2021). The SDM outputs for individual species were stacked based on their flowering months to obtain grids of monthly availability of a number of flowering forage species per grid cell (identified as *richness* in Chapter 6). An example of a S-SDM showing *richness* of bee forage species within the SWWA is presented in Figure 15.

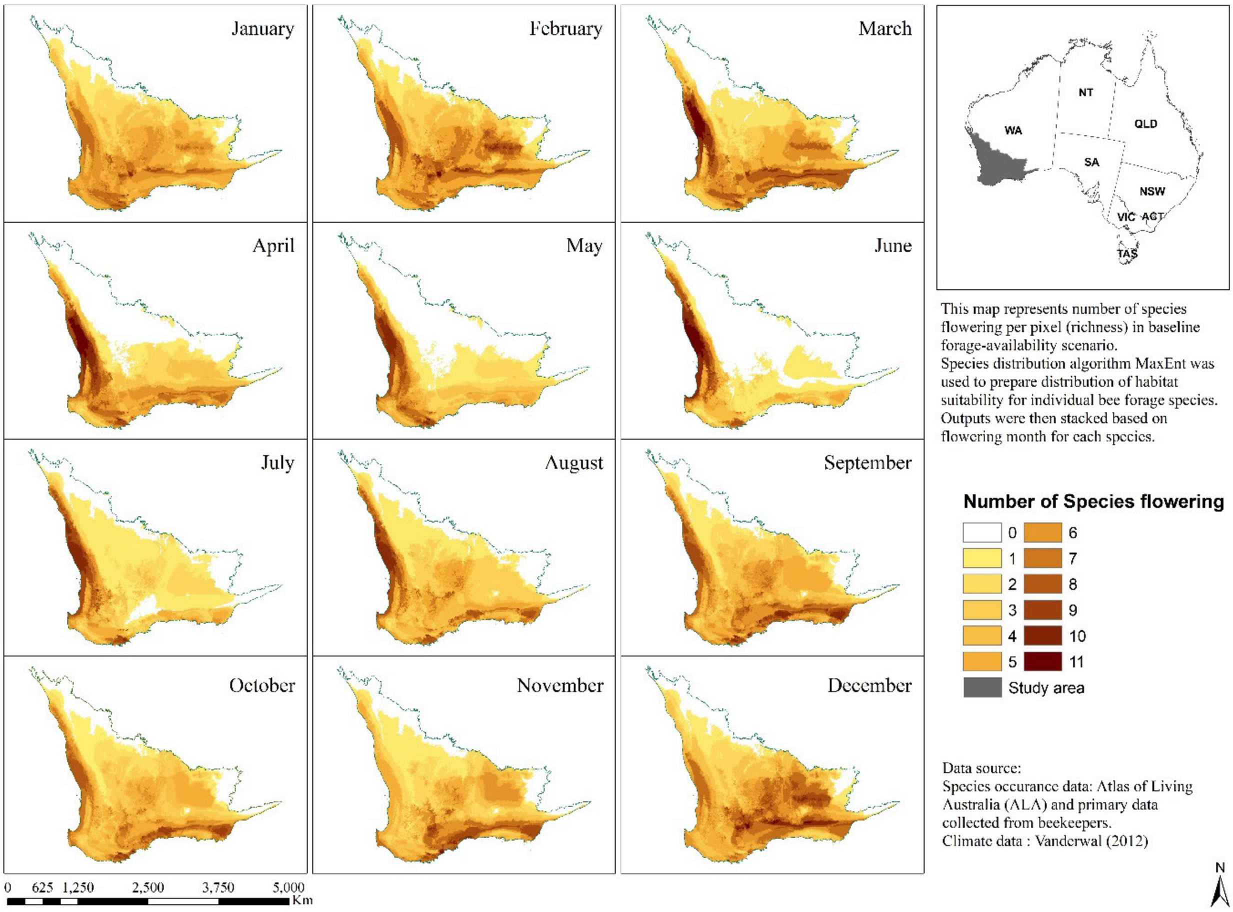


Figure 15: Spatial distribution of forage availability (richness of bee forage species) in Southwest Western Australia in baseline scenario. Darker colours represent greater numbers of species flowering within a pixel (high species richness).

Here, using a S-SDM provides an important understanding of the monthly distribution of bee forage species richness in SWWA. Here, it is important to note that these results are purely based on climatic suitability and do not take into account land clearing for agriculture and urban expansion. However, land clearing has been accounted for before using the S-SDMs in *B-Agent.* Further details about how these forage-availability layers are included in *B-Agent* to explain how the impacts of climate change on individual species results in variable forage-availability patterns, and how the variation in availability influences the spatial patterns of beehive migration in WA is presented in the following chapter.

5.6. Conclusion

Forage landscapes play a critical role in the sustainability of a beekeeping system. Climate change affects bee forage species by changing the geographic distribution ranges. Assessing the impacts of climate change on forage species is important for understanding impacts on the structurally interconnected beekeeping system. The Maxent species distribution model was used to predict the future distribution of 30 bee forage species. Results suggested that current distribution ranges are contracting for the majority of species used in this study with future distributions showing a poleward shift. Rainfall is the key contributor in predicting future distributions of bee forage species. Stacked SDMs provide an opportunity to understand current and future distributions of forage-availability for beekeeping activities, which can be further used to understand the dynamics around forage related migratory behaviours (Holloway, 2018).

Chapter 6: B-Agent: A hybrid modelling approach for assessing the influence of variation in forage availability on spatial patterns of beehive migration

Abstract

Bees and beekeeping are increasingly recognised as important contributors to sustainable development. Beekeeping is a landscape-scale process that involves complex interconnectivities between beekeepers, beehives and bee forage. Yet, accounting for these interactions within beekeeping system models is challenging as interactions are dynamic and often influenced by human behaviour and decision making. To this end, this research describes a spatially explicit hybrid agent-based model – *B-Agent*, which utilises multiple stakeholder engagement approaches to derive rules governing beekeepers' decision making processes and hybridises a machine-learning algorithm to build forage availability scenarios with an agent-based model to simulate beehive migration processes. The Western Australian beekeeping sector provides a case study for model development and testing to examine changes in (i) distances travelled by beekeepers, (ii) the frequency of beehive migration, and (iii) the spatial distribution of harvest locations resulting from climate related impacts on forage availability. The approach provides an evidence-base for better-informed management decisions in order to improve the long-term sustainability of beekeeping systems in Western Australia any beyond.

6.1 Introduction

Humans and their interactions with natural systems are embedded in a social-ecological system (SES) (Ostrom, 2009). In today's society, environmental change is ever-threatening the sustainability of SESs (Turner II et al., 2016). Characterising and modelling complex SES interconnectivities is becoming a new norm for effective environmental management, and the demand for new transdisciplinary approaches to support sustainable system initiatives is increasingly apparent (Davis et al., 2019; Rissman & Gillon, 2016; Virapongse et al., 2016). SES interactions are driven by human actions (e.g., economic activities) and explicitly incorporating human behaviour and decision-making into SES modelling is crucial to address sustainability challenges (Finn Müller-Hansen et al., 2017).

Beekeeping is a unique SES with potential for significant contribution towards achieving sustainable development goals (Patel et al., 2020). Migratory beekeeping requires access to quality forage resources to maintain healthy and productive bee colonies (Pilati & Fontana, 2018). This intrinsic interconnectivity between the state of the environment (forage landscape) and the beekeeper (managing colony productivity) highlights the need for ensuring sustainability of this SES to safeguard numerous ecosystem services provided by beekeeping and the forage landscape (Fedoriak et al., 2021; Malkamäki et al., 2016; Patel et al., 2020; Pilati & Fontana, 2018; Sponsler & Johnson, 2015).

While the biophysical state of the forage landscape affects all beekeeping, migratory beekeeping is specifically vulnerable to a multitude of environmental management decisions that affect forage resource quality, availability, and accessibility (Hoover & Hoover, 2014; Patel et al., 2020; Pilati & Prestamburgo, 2016; vanEngelsdorp & Meixner, 2010). In addition, global sustainability challenges, particularly that of a changing climate, affect bee colony responses (Flores et al., 2019), production from beehives (Delgado et al., 2012), and spatial-temporal mobility patterns within the beekeeping system (Castellanos-Potenciano et al., 2017).

A complete understanding of spatial patterns in SESs requires assessing human behaviours that influence these patterns (Ye & Mansury, 2016), as decision-making by beekeepers to select suitable forage sites for beehive migration results in spatial patterns of mobility and forage resource use. An integrative modelling approach, which is capable of incorporating data and modelling techniques across scales, disciplines, and levels of organisations has been deemed essential (Zvoleff & An, 2014). Agent-based modelling (ABM) is highlighted as a structurally integrative modelling approach that allows for incorporating human behaviour and interactions among individual entities to assess system-level emergent patterns (Gallagher et al., 2021; Kelly et al., 2013; Le Page et al., 2017; Lindkvist et al., 2020; Parker et al., 2003; Zvoleff & An, 2014). ABMs have been extensively used in studies of agricultural sustainability and related activities (Susnea et al., 2021), yet interactions associated with migratory beekeeping have only partially been explored.

For example, the BEEHAVE ABM, provides a representation of beekeeping practices but is limited to scenario modelling of Varroa mite parasite treatments (Becher et al., 2014). Similarly, an ABM of social-ecological interactions in beekeeping systems forms the basis of Johannsen et al. (2021)'s research, yet beehive migration processes are left unexplored. Several models exist for examining the various aspects of the beekeeping SES within the spatial context of agricultural landscapes and primary crop production (Becher et al., 2014; Champetier et al., 2014; Johannsen et al., 2021; Pilati & Fontana, 2018) providing important insights into managing bees within agriculture landscapes. However, in reality, the management of beekeeping systems within natural landscapes, such as forests, is more complex due to the diversity of forage resources accessible to bees and beekeepers as well as the multifunctional nature of these forage landscapes.

Given these reflections, an evident research gap presents a need to address modelling system behaviour within the bee industry; assessing how changing biophysical elements (forage landscape) are associated with changing human behaviour and resultant spatial mobility patterns is critical for the ongoing sustainable management of beekeeping systems. To this end, the research presented here results from the development of an ABM of the beekeeping system, specifically focused on migratory beekeeping within highly biodiverse natural landscapes. We develop a hybrid modelling approach to represent beekeeper-beehive-forage landscape interactions. Using our model *B-Agent*, we assess spatial patterns of beehive migration in the state of Western Australia (WA), and describe how climate-induced changes in forage availability may influence patterns in future beekeeper mobility. Our methods contribute to filling the gap in modelling hive migration behaviour that has not been included in previous ABMs representing beekeeping SESs. This research provides bee industry stakeholders with a new tool to assess the impacts of environmental pressures on the beekeeping SES, helping to inform resources management decision-making and facilitating the contributions of beekeeping for achieving sustainable development.

6.2 Materials and Methods

6.2.1 Study location: Western Australia

The WA beekeeping system relies on access of key bee forage species from the Myrtaceae and Proteaceae families found in the southwest region of the state; an internationally recognised biodiversity hotspot (Benecke, 2007; Myers et al., 2000; Roshan et al., 2017; Smith, 1969). The study extent of this region covers 478,400 km^2, including 18 biogeographic subregions, each with a unique combination of bee forage species (Figure 16). A range of *Eucalyptus* and *Banksia* species form a strong forage resource base for the state's bee industry. In particular, Jarrah (*Eucalyptus marginata)* and Marri (*Corymbia callophylla*) are sought after for monofloral honey production aiming for high economic return due to their unique flavour, texture and medicinal properties (Manning, 2011; Roshan et al., 2017; Soares et al., 2017).

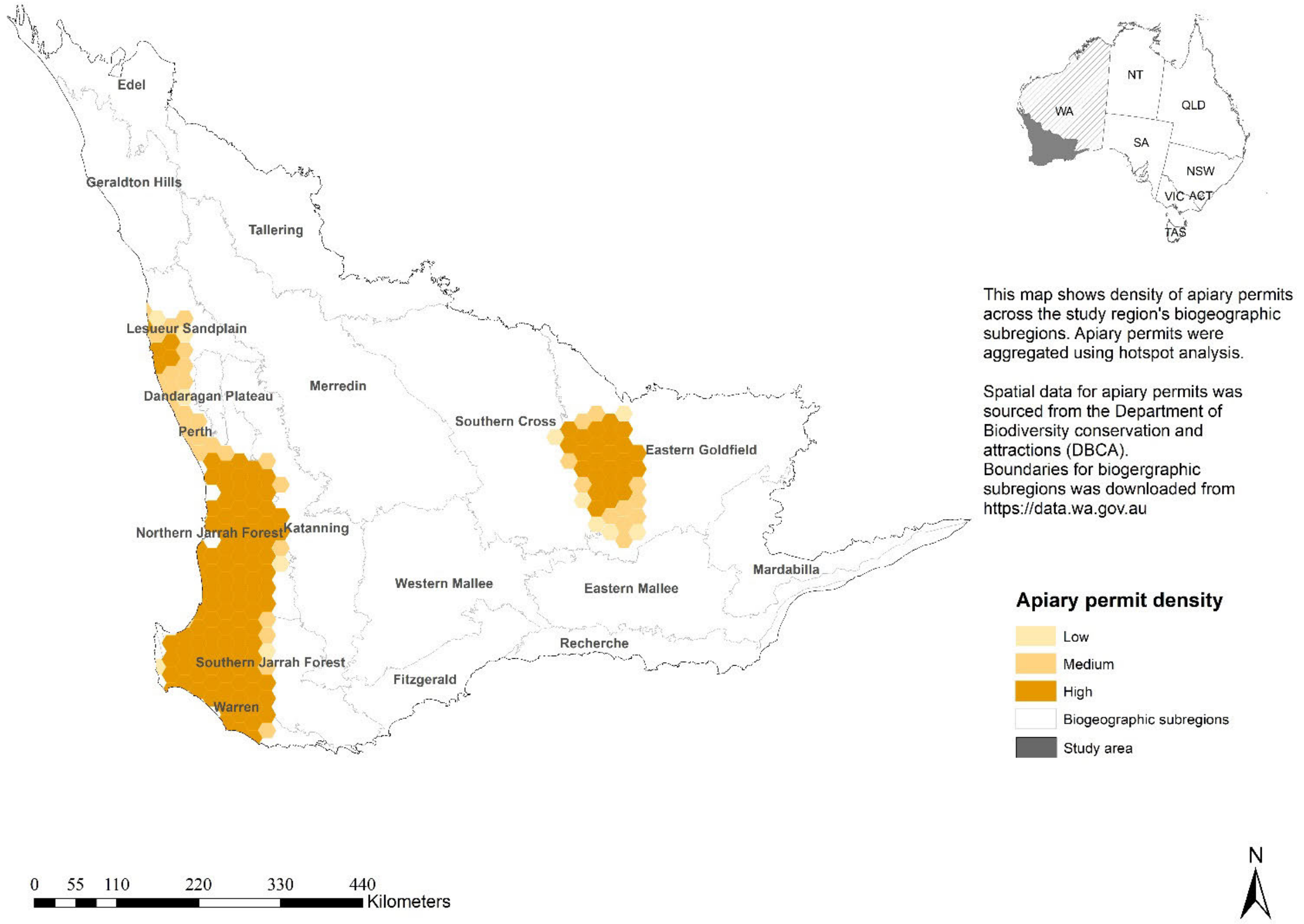


Figure 16: Study area map representing the density of apiary permits across the 18 biogeographic subregions in Western Australia. High, medium and low densities correspond with statistically significant clusters (hotspots) of apiary permits across the region.

In WA, commercial beekeeping is migratory, which involves accessing a sequence of forage sites from government and privately owned land. Beekeepers negotiate access to forage site with private landowners. However, to place hives on government land, beekeepers are required to obtain an apiary permit (Figure 16). Following strict biosecurity regulations, a 3 km distance is required between each permitted apiary site (DBCA, 2013).

Beekeepers' knowledge and decision-making plays a critical role in selecting a forage site to maximize gain (i.e., profitability) and optimise bee colony health (Johannsen et al., 2021; Pilati & Prestamburgo, 2016). Spatial-temporal availability of flowering forage resources in the landscape, access to key bee forage species and travel required to access forage locations (e.g., proximity to home location), have been identified as the main factors affecting the decision-making of beekeepers for migrating hives (Patel et al., 2020; Pilati & Fontana, 2018; Sarı et al., 2020; Zoccali et al., 2017). With regards to environmental impacts affecting migration behaviour, Patel et al. (2020) notes three priority pressures in WA: (i) availability, access and utilization of forage sites; (ii) burning of forage resources; and, (iii) climate change. While these, and all, pressures on beekeeping systems are interconnected, the impacts of climate change on the forage resource base have been widely evidenced; for example, habitat loss in *Eucalyptus* spp. (Booth, 2017; Gonzalez-Orozco et al., 2016; Hamer et al., 2015) and range contraction in *Banksia* spp. (Fitzpatrick et al., 2008; Yates et al., 2010) have been well documented.

A change in resource base (i.e., forage availability) for migratory beekeeping affects the spatial patterns of beehive migration and associated outcomes (Castellanos-Potenciano et al., 2017; Delgado et al., 2012; Patel et al., 2020; Pilati & Fontana, 2018), and an examination of these changes holds the potential to inform integrated resource management initiatives. As such, the applied research aim of this paper is to examine the spatial patterns of beehive migration and the changes relative to alterations in forage availability, addressing the following objectives and research questions:

1. Identify the spatial extent and species composition of current and future forage availability for beekeepers.
   (i) What are the key bee forage species targeted by beekeepers in WA?
   (ii) What are the current spatial distributions of the key bee forage species?
   (iii) Under proposed future climate projections, what are the modelled spatial distributions of the key bee forage species?
   (iv) How do the predicted extents of future distributions of key bee forage species differ spatially to present day?

2. Determine the spatial patterns of beehive migration using baseline and future modelled forage availability scenarios.
   (v) What are the current spatial patterns of beehive migration?
   (vi) How does the current spatial patterns of beehive migration in the future based on changes in forage-availability?
   (vii) What is the spatial distribution of locations harvested by beekeepers now and in the future based on changes in forage-availability?

6.2.2 *B-Agent* design concept

B-Agent provides a methodology to address the research aim to understand the dynamic social-ecological interactions around beehive migration behaviour. *B-Agent* represents a hybrid modelling approach based on social-ecological theory, modelling beehive migration as a key social-ecological interaction associated with beekeeping systems. *B-Agent* integrates (i) multiple stakeholder engagement methods used to determine key bee forage species, define model interaction rules, and identify key SES patterns (ii) a machine learning algorithm (using MaxEnt software) to develop forage availability scenarios, and (iii) a hive migration ABM (implemented in NetLogo) for modelling beehive migration behavioural decisions. Figure 17 illustrates the workflow of the modelling approach.

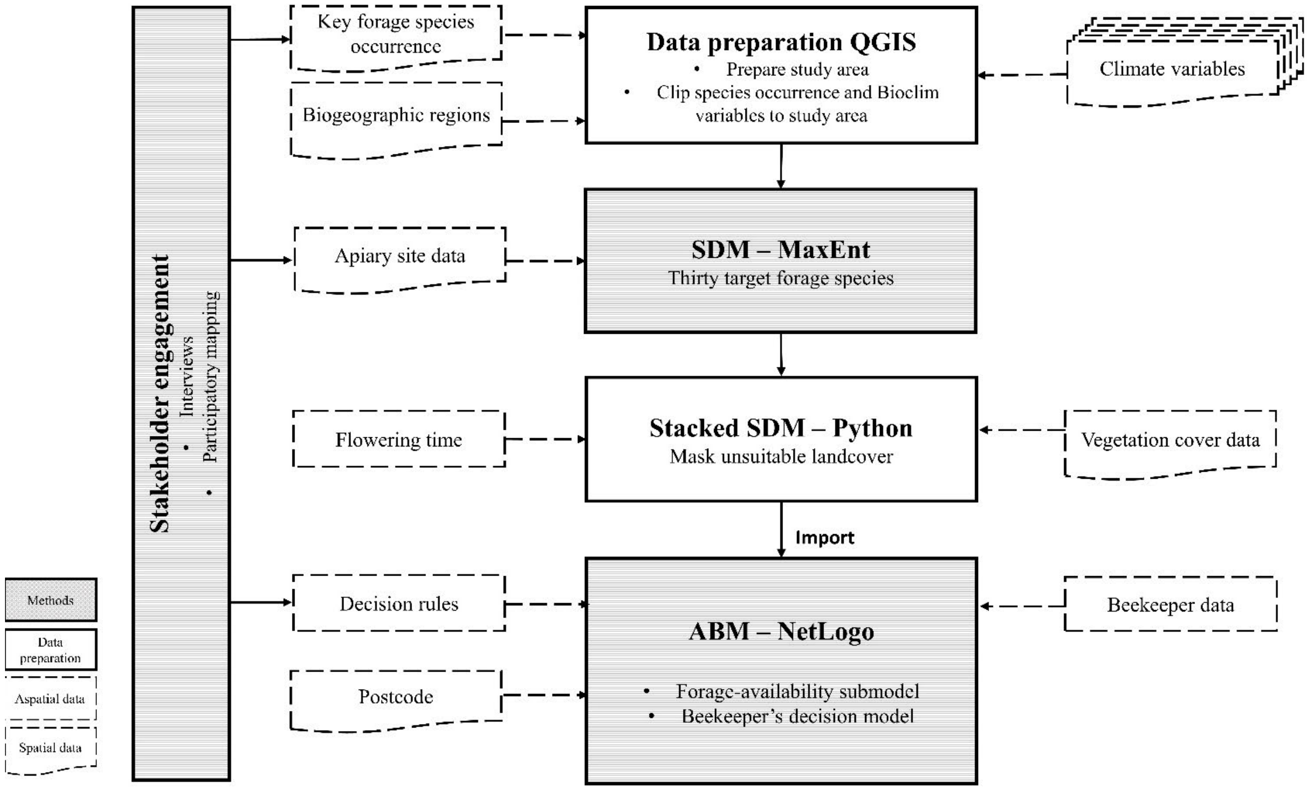


Figure 17: B-Agent workflow where multiple data sources and methods including stakeholder engagement, machine learning and agent-based modelling are combined to build an integrated model. Grey shade represents key methods, whereas white boxes represent data preparation stages. Shapes and dashed lines represent spatial and aspatial data.

6.2.2.1 Identifying key forage species

To identify the forage species targeted by apiarists, semi-structured interviews were conducted with 29 commercial beekeepers (with more than 50 hives) following UWA human ethics approval (RA/4/1/9247). The participants were selected with the help of the Bee Industry Council of Western Australia (BICWA). From the interview data, bee forage species (n = 30; Table 7) targeted by beekeepers were shortlisted and the factors influencing beekeepers forage site selection were identified. Flowering times (months of the year) for the shortlisted species were obtained from the Florabase (https://florabase.dpaw.wa.gov.au). Key species including Jarrah (*Eucalyptus marginata*) and Marri (*Corymbia callophylla*), which are targeted for monofloral honey production (Patel et al., 2020) were identified as 'premium' species. Peak flowering months for these 'premium' species were obtained from French et al. (2019) to include increased temporal precision.

Beekeeper data including, residential addresses and number of hive ranges (i.e., 50 – 99, 100 – 499, 500 – 999 and 1000+) was collected from the WA state government Department of Primary Industries and Regional Development (DPIRD). Boundaries for beekeepers' residential postcodes[6] (i.e., 88 postcodes) were extracted from Australian postcode boundaries (downloaded from Australian Bureau of Statistics (https://abs.gov.au)) for use as input into hive migration ABM (see section 6.2.2.3). The coordinates for each apiary permit owned by a participant beekeeper were collected from the WA state government Department of Biodiversity, Conservation and Attractions (DBCA). A Participatory Geographic Information System (PGIS) mapping approach was then used with each interviewee to identify specific target species and to rank each permit site by preference. Preference ranks ranged from 1 – 9 (9 being the most important site for the individual's beekeeping operation and 1 being least important) and reflected the importance of the forage species accessed at a particular site. Standardisation of species names required the use of historic literature (Leech, 2012; Smith, 1969) and expert knowledge as participants sometimes reported traditional Indigenous names for target species, e.g., the local Noongar language word 'Boongul' for the species *Eucalyptus transcontinentalis* (Abbott, 1983).

[6] Over 50% of the population of beekeepers with 50 or more hives reside within the Perth metropolitan region based on the residential addresses of commercial beekeepers.

Table 7: The 30 most frequently reported bee forage species targeted by beekeepers in Western Australia. Table cells with ✓represents flowering months for the species (https://florabase.dpaw.wa.gov.au). Species in bold represent two premium species Jarrah and Marri with ✓✓representing their peak flowering times (French et al., 2019).

Species Name	Common Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Banksia attenuata	Candle banksia/Yellow banksia/Slender banksia	✓	✓					✓			✓	✓	✓
Banksia menziesii	Firewood banksia/Red banksia/Menzies banksia		✓	✓	✓	✓	✓	✓	✓	✓	✓		
Banksia sessilis	Parrot bush				✓	✓	✓	✓	✓	✓	✓	✓	
Banksia sphaerocarpa	Fox Banksia	✓	✓	✓	✓	✓	✓	✓					
Calothamnus quadrifidus	One-sided bottlebrush						✓	✓	✓	✓	✓	✓	✓
Corymbia callophylla	Marri/Red gum/Port gregory gum	✓✓	✓✓	✓✓	✓	✓		✓					✓
Eucalyptus accedens	Powderbark wandoo	✓	✓	✓	✓			✓					✓
Eucalyptus annulata	Open-fruited mallee							✓	✓	✓	✓	✓	✓
Eucalyptus burracoppinensis	Burracoppin mallee							✓	✓	✓	✓	✓	
Eucalyptus cornuta	Yate	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	
Eucalyptus diversicolor	Karri	✓	✓			✓		✓		✓	✓	✓	✓
Eucalyptus dundasii	Dundas blackbutt		✓	✓	✓	✓		✓					
Eucalyptus flocktoniae	Merrit	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Eucalyptus incrassata	Lerp mallee/Yellow mallee	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Eucalyptus lesouefii	Goldfields blackbutt	✓	✓					✓	✓	✓	✓	✓	✓
Eucalyptus longicornis	Red morrel/Morrel	✓	✓					✓					✓
Eucalyptus loxophleba	York gum	✓	✓					✓	✓	✓	✓	✓	✓
Eucalyptus marginata	Jarrah	✓					✓	✓	✓	✓✓	✓✓	✓✓	✓
Eucalyptus melanoxylon	Black morrel	✓	✓	✓	✓	✓		✓					✓
Eucalyptus occidentalis	Flat-topped yate/Swamp yate	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓
Eucalyptus platypus	Moort	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓
Eucalyptus ravida	Bronze & silver gimlet							✓		✓	✓	✓	✓
Eucalyptus redunca	Black marlock/Mallee form of Wandoo							✓			✓	✓	
Eucalyptus salubris	Gimlet	✓	✓	✓				✓		✓	✓		✓
Eucalyptus stricklandii	Strickland's gum	✓	✓	✓				✓				✓	✓
Eucalyptus transcontinentalis	Redwood							✓	✓	✓	✓	✓	✓
Eucalyptus wandoo	Wandoo/White gum	✓	✓	✓	✓	✓		✓					✓
Hakea trifurcata	Two-leaf hakea/White bush/Kangaroo				✓	✓	✓	✓	✓	✓	✓		
Leucopogon conostephioides	May flower/White bell			✓	✓	✓	✓	✓	✓	✓	✓		
Leucopogon oldfieldii	Oldfields beard-heath			✓	✓	✓	✓	✓	✓	✓	✓		

6.2.2.2 Species distribution modelling (SDM) of key bee forage species

6.2.2.2.1 Species spatial extent

The distribution of bee forage species can provide spatial-temporal insights into important bee habitat which plays a critical role in beehive migration behaviours. A machine learning algorithm MaxEnt (Phillips, Anderson, et al., 2006) was used to obtain the geographic distributions of key bee forage species. MaxEnt uses presence-only data and background (pseudo-random) points randomly distributed across the study extent to estimate the closest to uniform (maximum entropy) distribution for a range of independent environmental variables (Elith & Graham, 2009). Species occurrence data for the 30 shortlisted species were downloaded using the spatial portal Atlas of living Australia[7] (https://spatial.ala.org.au). Occurrence records were clipped using the study area boundary, prepared from spatial data for the Interim Biogeographic Regionalisation for Australia (IBRA) (https://www.environment.gov.au/). Participatory GIS mapping data was used to identify additional species occurrence samples aiming to overcome spatial bias in ALA records (Fithian et al., 2015; James et al., 2018). To this end, apiary permit locations were classified based on the primary species targeted at each location to provide additional occurrence records for each of the forage species listed in Table 7. GIS vector files (shapefiles) from ALA and participatory GIS mapping were merged in QGIS 3.10 to compile occurrence points for each species, which were then sampled as 70% training and 30% test data for species distribution modelling in MaxEnt version 3.4.1.

MaxEnt uses a list of species presence-only data, a set of environmental predictor grids (e.g., temperature, precipitation) as inputs and generates a random distribution of background absence samples (often-called pseudo-absences) across the study area to produce a species probability distribution with 'maximum entropy' (i.e., closest to uniform or most spread out) by contrasting the

[7] Atlas of Living Australia (ALA) is a platform for providing open source biodiversity data covering over 85 million records of more than 111,000 species, aggregated from multiple sources and citizen science across Australia (ALA, 2020). Bias in ALA data has been recognised in the literature with the recommendations for approaches such as additional sampling and digitizing to overcome data quality gaps (James et al., 2018).

environmental conditions at the background locations with those at observed presence locations (Elith et al., 2011; Merow et al., 2013; Phillips, Anderson, et al., 2006). Maxent builds highly non-linear response curves using six feature functions: linear (variable itself), product (product of two variables), quadratic (square of variables), hinge (similar to piecewise linear spline), threshold (similar to piecewise constant spline), and categorical (binary indicator) (Elith et al., 2011).

SDMs for each individual species were calculated using 10,000 pseudo-random points and six bioclimate variables to obtain the logistic outputs for each species. The logistic output raster for each species provides an estimation for the probability of presence (between 0 (lowest probability) and 1 (highest probability)) of the species across the study area (Elith et al., 2011; Phillips, 2005). To increase model performance, only 'hinge features' were used (Gonzalez-Orozco et al., 2016; Phillips & Dudík, 2008). The outputs for each species were evaluated using threshold-independent the area under the receiver operating characteristic curve (AUC) statistic from a fivefold cross-validation. The results for individual forage species are provided in Appendix 5.

6.2.2.2.2 Climate scenarios

Two climate scenarios for modelling baseline and future forage availability were developed for use in B-Agent. The baseline scenario represents Bureau of Meteorology climate datasets (1976 – 2005) prepared for Australia and used for climate projects (http://www.bom.gov.au/jsp/awap/). This included 19 bioclimate variables for the time period at 1 km spatial resolution. As almost 70% of the target bee forage species (Table) represent eucalypt species, the selection of emission scenario and GCM was guided by the literature representing applications of MaxEnt on multiple eucalypt species in Australia including Hamer et al. (2015) and Gonzalez-Orozco et al. (2016). In particular, the future scenario uses data from the moderate emission Representative Concentration Pathway (RCP) 6.0 scenario for the Global Climate Model (GCM) CSIRO Mk3 for the year 2055. Bioclimate data prepared for Australia (Vanderwal, 2012) were obtained for the 19 bioclimate variables, which represent data across the time period (2015 – 2085) at 1 km spatial resolution. To minimize multicollinearity, six of these predictors including, Isothermality (Bio3), Maximum temperature of the warmest month (Bio5), Mean temperature of coldest quarter (Bio11), Annual precipitation (Bio12), Precipitation of wettest quarter (Bio16) and Precipitation of driest quarter (Bio17) were selected for use in MaxEnt modelling. The variable selection was based on the Pearson correlation coefficient ($r > 0.7$ and $r < -0.7$) and prior SDM studies for species listed in Table 7 (Gonzalez-Orozco et al., 2016; Hamer et al., 2015).

6.2.2.2.3 Developing Forage availability scenarios

Distributions for the 30 individual target forage species were obtained for both baseline and future[8] scenarios using the SDM. A maximum training sensitivity plus specificity logistic threshold was used to convert habitat suitability into presence/absence rasters for each species (Gonzalez-Orozco et al., 2016; Hamer et al., 2015). Species distribution rasters for 30 species were then combined based on their flowering times (Table 7) to produce stacked species distribution models (S-SDMs) per month in Python. S-SDMs resulted in 12 monthly rasters (January to December) each representing the number of forage species flowering per pixel for the corresponding month (i.e., species richness as defined in Kiester (2013)). To ensure the S-SDMs provided a realistic spatial distribution of system forage locations, all areas of cleared vegetation (Bradshaw, 2012), non-native vegetation, and buildings as identified using the National Vegetation Information System (NVIS) data (https://www.environment.gov.au/fed, accessed June 2021) were used as a spatial mask, which removed 37.5% of the total study area. The same process was repeated to prepare S-SDMs for the two premium species using peak flowering times (Table 7). This resulted in total 48 masked S-SDMs (i.e., 24 raster representing each scenario). These 48 rasters were then reprojected using a projected coordinate system (WGS 84 / UTM zone 50S) and resampled to a 3000 m × 3000 m cell size to maintain the biosecurity regulation for apiary sites (highlighted in section 6.2.1), before use

[8] Here, the future scenario reflects the Representative Concentration Pathway (RCP) 6.0 scenario for the Global Climate Model (GCM) CSIRO Mk3. Bioclimatic predictor Isothermality (Bio3), Maximum temperature of the warmest month (Bio5), Mean temperature of coldest quarter (Bio11), Annual precipitation (Bio12), Precipitation of wettest quarter (Bio16) and Precipitation of driest quarter (Bio17) were used in MaxEnt. An additional high emission future scenario (RCP8.5) was used to test the robustness of *B-Agent.* The results of individual SDMs and ABM outputs in all scenarios are provided in Appendix B.

as inputs in NetLogo to initialise the baseline and future forage availability environments for the hive migration ABM.

6.2.2.3 Hive migration Agent-based model

The overall purpose[9] of the hive migration ABM was to understand how the variability in spatial patterns of forage availability (i.e., the S-SDMs) may influence beehive migration decisions and associated patterns across the year. Beehive migration patterns generally follow the spatial-temporal availability of bee forage that influences the economic outcomes of honey production and pollination services (Pilati & Fontana, 2018). Travel distance associated with hive migration contributes to the health of bee colonies (Alger et al., 2018; Melicher et al., 2019) but results in fuel costs associated with moving hives from one location to the next (Patel et al., 2020). Spatial patterns used to evaluate the hive migration ABM include current patterns of forage site use identified during PGIS mapping sessions such as frequency of hive movement, and distance travelled by beekeepers to access quality forage. NetLogo 6.2.0 was used to develop the hive migration ABM (code is provided in Appendix 6). NetLogo was selected for its ease of use, built-in GIS extension for spatial modelling and supporting user community.

6.2.2.3.1 Entities, state variables, and scales

The hive migration ABM includes three entities: forage availability cells (spatial grid), beekeepers, and loads (of beehives). Agents represent both beekeepers and loads (1 load = 90 – 100 beehives in the WA beekeeping system). Load agents are linked to their owner (a beekeeper) through the load variable *load_id.* Each beekeeper identifies their loads (*my_loads*) and the number of loads (*num_loads*) owned, which characterises a beekeeper agent as *commercial* (*num_loads* > 4) or *semi-commercial* (*num_loads* < 5). The forage landscape is presented as a series of spatial grids

[9] The ODD (Overview, Design concepts, Details) protocol (Volker Grimm et al., 2010), as updated by Volker Grimm et al. (2020) is used here to describe the hive migration ABM, and decision-making processes are described following the guidelines provided by Müller et al. (2013). A detailed ABM description including a description of the submodels is provided in Appendix 7).

with each cell representing a ground area of 9 square kilometres. Each cell has a set of variables that initialise based on the pixel values of 24 input rasters, which comprise 12 *richness* rasters (*jan – dec*) of bee forage species, and 12 *premium species* rasters (*janP – decP)*; one per month. The model uses discrete time steps, where one time step represents one month, and the model runs for a duration of 12 months for each selected forage availability scenario (i.e., baseline and future). All model entities have a set of variables that are updated every time step, as listed in Figure 18.A. The 'state' variables updated every time step are discussed in the following sections. Detailed information on each is provided in Table 7.2 in Appendix 7.

6.2.2.3.2 Initialising agents and environment

To initialise the model, it first imports GIS boundaries for the study area as well as residential postcodes, and forage availability rasters into NetLogo and creates a subset of NetLogo patches (*model_patches*) within the study area boundary (Figure 18A). Next, according to available beekeeper data, the number of beekeepers and loads are initialised randomly within a corresponding postcode to retain anonymity. The forage availability environment is then initialised where each patch is attributed with forage availability information (*availability_months*) including richness of bee forage species (*sp_rich*) and availability of premium species (*sp_premium_months*) for each month of the year based on the values of 24 input rasters (24 at baseline and 24 at future). The general model framework is presented in Figure 18B. Starting from August (the beginning of the honey season) forage-related patch variables are updated each month (see Section 6.2.2.3.3); beekeeper agents then execute the decision-making sub-model (see Section 6.2.2.3.4) (*update_targets*) to identify new target forage sites if migration is required. The run ends after twelve months.

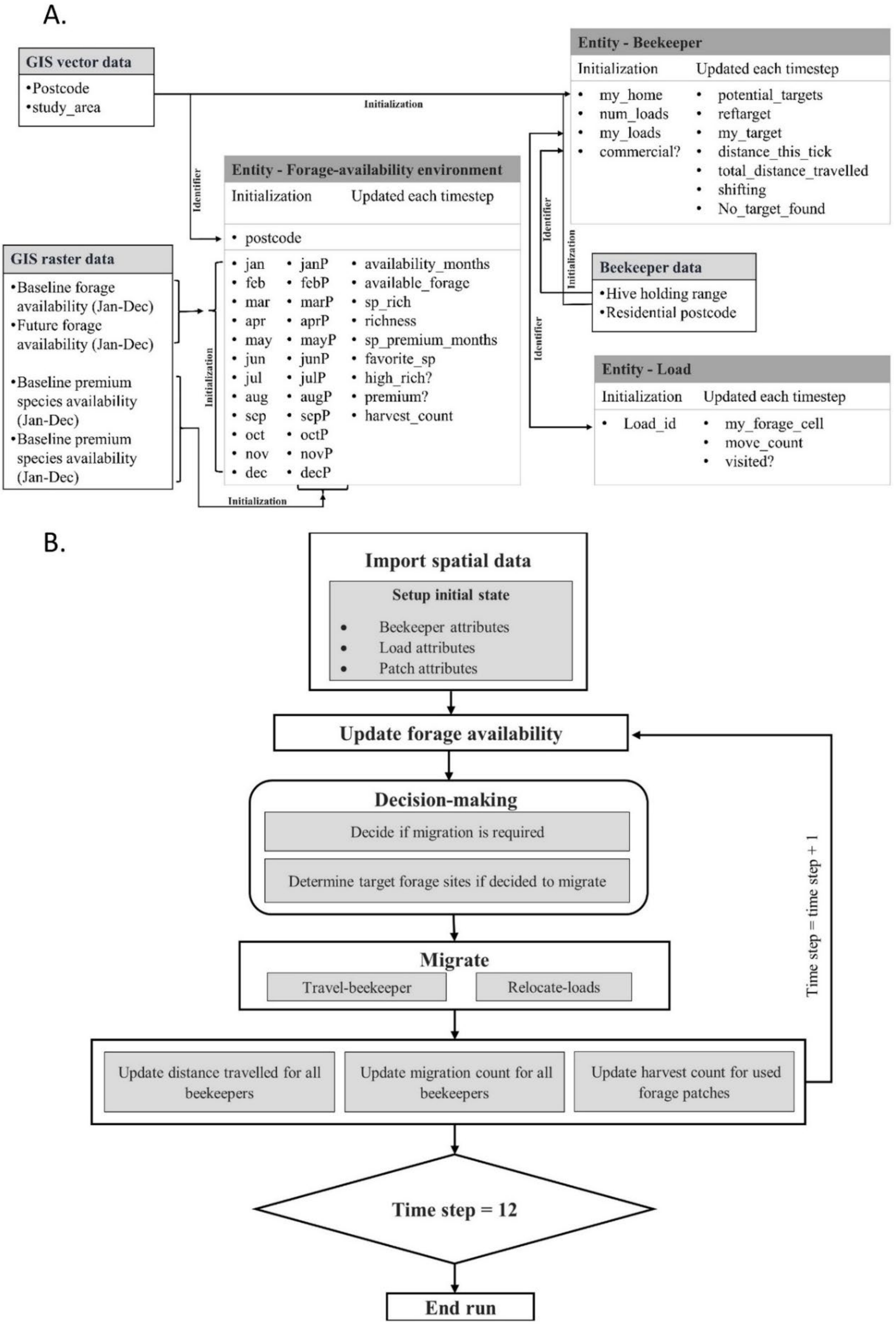


Figure 18: Overview of the Hive migration ABM embedded in B-Agent. (A) Schematic of entities and state variables, where arrows highlight data used to initialize state variables and relationship for each entity. (B) Workflow representing key processes and scheduling.

6.2.2.3.3 Forage availability submodel

At each time step, the values of the number of flowering forage species and flowering premium forage species are updated (i.e., *available_forage, richness* and *sp_premium*) for each patch corresponding to the current time step. The patches with high species richness[10] (i.e., *richness > 3*), and patches with flowering forage availability of premium species [11](*sp_premium > 0*) are identified. The three patch variables correspond to flowering forage availability, the richness of flowering species and availability of flowering premium species are fundamental for initialising the beekeepers' decision-making submodel.

6.2.2.3.4 Decision-making submodel

The decision-making submodel for beekeeper agents reflects satisficing heuristics in bounded rationality (Todd & Gigerenzer, 2000) whereby beekeeper agents know everything about their environment for the current time step and evaluate available options to maximize gain from a forage site with minimum travel. A beekeeper agent locates a new forage site (*pick_new_targets*) once the forage resources at the beekeeper agent's initial patch (*my_home*) becomes zero. Since one forage patch can only serve one load, beekeepers with more than one load find new forage sites despite possibly having forage availability at their home patch (note: as described previously, the beekeepers' home patch corresponds to a 3000 m × 3000 m NetLogo patch within their residential postcode boundary, from where the beekeeper is initialized). At each time step, a beekeeper agent identifies potential targets (*potential_targets*) as patches with forage availability (*available_forage = 1*). Here, semi-commercial beekeeper agents limit their search according to the maximum distance (*proximity*) they are willing to travel from their home, which is set to a maximum of 300 km, a threshold selected based on interview data.

[10] The value for *richness* was determined by hive site rankings collected from during participatory mapping exercises with commercial beekeepers, where higher rankings were given to sites with more than three forage species available.

Beekeeper agents unable to find any potential targets move back to their home patch (*my_home*). Although this decision involves additional travel, it does not give unrealistic travel distances associated with beehive migration; only one trip to the forage site is accounted for in the ABM, in contrast to the multiple trips experienced in reality (e.g., checking a forage site before moving hives and checking hive performance). A beekeeper agent that identifies a new target site (*potential_targets*) then evaluates migration to that site using the if-then rules, where sites with premium species are the first priority followed by sites with high richness as a second priority. In a case where sites with none of these priorities are available beekeepers choose any site with forage resource available (*available_forage = 1*). Beekeeper agents then identify one patch as a reference patch (*reftarget*) from the set of potential targets (*my_targets*).

In addition to suitable forage sites, the maximum distance between individual loads (*spread*) placed on multiple forage sites significantly contributes to maximising the gain from a migration sequence as accessing a cluster of sites may reduce inter-load travel. Beekeepers use their reference patch (*reftarget*) to find a number of forage sites (*my_targets*) clustered within the distance (*spread*) between their loads. The value of spread is determined as 20 km following interview responses and GIS analysis of participatory mapped distances between individual beekeepers' apiary site clusters. If beekeeper agents cannot find clustered targets for all loads at once, they search for two smaller clusters that can accommodate a proportion (*split*) of their number of loads (*num_loads*) to each.

When forage availability (*available_forage*) at the location of a load agent becomes zero, the load is relocated (*relocate_load*), here each load agent uses their owner beekeeper agent's reference patch (*reftarget*) to identify a new forage site (*my_forage_cells* – equivalent to *my_targets* for each beekeeper) following their owner's decision model. Load agents then move to a selected forage cell (*my_forage_cells*) and update the value of their movement count (*move_count*) by adding each move to the count of previous moves (*move_count = move_count + 1*). From the reference patch (*reftarget*), the beekeeper agents move to the closest loads using a nearest neighbour algorithm. In each time step, beekeeper agents update the value of total distance travelled (*total_distance_travelled*) as accumulated distance travelled during each time step (*total_distance_travelled* = *total_distance_travelled* + *distance_this_tick*). The travel distance is calculated as a Euclidean distance between two patches using the following equation:

$$d(P_1,P_2) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

Where d = Euclidean distance between two patches; P_1 = Current Patch; P_2 = Target Patch; x_1, y_1 = patch coordinates of current patch; x_2, y_2 = patch coordinates of target patch. Beekeepers update their migration frequency (*shifting*) as load agents' average movement count (*move_count)* and update the value of patches used by their loads (*harvest_count)*.

6.2.3 B-Agent outcome measures, model evaluation, and validation

The *B-Agent* model outputs provide mapped spatial patterns in forage availability variables (i.e., species richness and premium species), as used in the decision-making model by beekeeper agents. Additionally, mobility patterns for baseline and future[12] scenarios are assessed. Mean raster values are calculated using Zonal statistics for the 18 biogeographic subregions (Table 8) to understand seasonal spatial distribution of forage availability. Statistically significant clusters of high and low forage availability were identified using hotspot analysis. Difference maps for all forage species (*richness*) and premium species (*sp_premium*) were created for each monthly S-SDMs of future forage availability relative to baseline forage availability in order to understand monthly changes in forage availability.

[12] The future scenario discussed in this case study represents the moderate emission (RCP6.0) scenario. An additional high emission future scenario (RCP8.5) was used to test the robustness of *B-Agent.* The results of individual SDMs and ABM outputs for all scenarios are provided in Appendix 5.

Mobility patterns were obtained from 100 runs of the model for each baseline and future scenario. Patterns in distance travelled by commercial and semi-commercial beekeepers were measured at the end of the run (*total_distance_travelled)* and at each time step (*distance_this_tick*). The output distance was multiplied by the cell size to report distance in kilometres. The hive migration frequency (*shifting)* of beekeeper agents is measured for all beekeepers and a raster representing hive site use (*harvest_count*) is exported at the end of each run. To understand the patterns in harvested locations, rasters for each run were aggregated using a 30 km hexgrid across study area. Mean centroid was calculated for both scenarios to understand harvest patterns.

The theoretical framework used to develop *B-Agent* was validated in our previous research Patel et al. (2020). The hive migration ABM was evaluated here using a pattern-oriented approach (POM) (Grimm et al., 2005) for its ability to reproduce known patterns in the WA beekeeping system, as reported in Patel et al. (2020), to recognize potential impacts from a changing climate on the WA beekeeping SES. Specific pattern-orientation ensured the: (i) mean annual distance travelled for the commercial beekeepers was always higher than semi-commercial beekeepers; (ii) annual frequency of beehive migration (maximum *shifting*) ranges was between two and six; and (iii) number of forage sites used in the future increased in the inland regions of the state.

In addition to the POM approach, model validation was carried out with 14 beekeepers (i.e., 7 commercial and 7 semi-commercial) for whom information on the sequencing of forage sites across a year (spring 2016 – spring 2017) was available. Within the hive migration ABM, the 14 beekeeper agents were initialized from their residential location within the postcode and classified as commercial or semi-commercial according to the number of hives held by each. The model was run multiple times to accommodate the partial variation in beekeepers' selection of target forage sites. The statistical significance of the model outputs was determined using the paired two-sample t-test and *p* value.

6.3 Results and discussion

6.3.1 Key species and spatial distribution of forage availability

Key bee forage species targeted by beekeepers in WA were identified in Table 6.1 and provide the focus for species distribution modelling used to describe forage availability across the southwestern portion of the state. Monthly and seasonal distributions in forage availability are provided in Appendix 5, Figures 5.1 and 5.2 at baseline, and Figures 5.3 and 5.4 for our future scenario. The results presented here provide important insights for understanding the interconnectivities between forage availability dynamics and beehive migration patterns. Our results are in agreement with other research findings whereby the importance of coastal forage areas in beehive migration behaviour has been highlighted (Albayrak et al., 2021).

6.3.1.1 Forage availability – baseline

In the baseline scenario, the Perth biogeographic subregion (refer to map in Figure 19) shows the highest average value for richness of bee forage species during all seasons, particularly in winter (22.0); when compared to all biogeographic subregions across the southwest of WA (Table 8). Esperance Plains also comprised higher levels of species richness during spring in the subregions of Fitzgerald (19.8) and Recherche (17.5). Statistically significant clusters of high species richness are found in the same biogeographic regions (i.e., Swan Coastal Plain and Esperance Plains) during all seasons (see Appendix 5, Figure 5.2). In autumn months, higher species richness was also observed in Lesueur Sandplain (16.4) and Northern Jarrah Forest (17.1) subregions. During spring and summer, higher species richness was observed in the eastern biogeographic regions including the Mallee and Goldfields subregions. The lowest species richness in all months was observed in Edel and Tallering subregions (Table 8). The extent of premium species was concentrated in the biogeographic regions of Swan Coastal Plain and Jarrah Forest, particularly during spring and summer (Appendix 5, Figure 5.1 and 5.2).

Table 8: Availability of key bee forage species in the 18 biogeographic subregions for baseline and future scenarios in Western Australia. Availability is indicated by the mean species richness value averaged for each subregion by season; spring (September-November), summer (December-February), autumn (March – May), and winter (June – August).

Biogeographic regions	Biogeographic subregion	Spring		Summer		Autumn		Winter	
		Baseline	Future	Baseline	Future	Baseline	Future	Baseline	Future
Avon Wheatbelt	Merredin	7.4	3.2	7.9	3.9	1.8	0.6	3.3	1.4
	Katanning	10.2	8.2	12.5	9.5	9.9	6.0	7.5	5.6
Coolgardie	Eastern Goldfield	7.5	4.0	8.4	4.6	3.3	2.0	1.9	1.3
	Mardabilla	4.9	3.8	6.3	5.3	5.2	4.4	2.0	2.0
	Southern Cross	8.6	4.6	10.3	5.2	3.6	1.8	3.2	2.1
Esperance Plains	Recherche	17.7	17.4	11.6	12.0	12.7	13.9	10.5	11.4
	Fitzgerald	19.8	19.9	14.2	14.1	12.7	13.5	9.3	10.2
Geraldton Sandplains	Lesueur Sandplain	13.3	7.7	11.0	7.0	16.4	8.1	16.8	9.6
	Geraldton Hills	5.9	1.9	4.3	1.5	3.0	0.8	6.0	2.2
Jarrah Forest	Southern Jarrah Forest	12.1	13.7	13.2	13.8	13.7	16.8	11.3	14.5
	Northern Jarrah Forest	12.8	13.8	14.0	15.6	17.1	19.7	15.6	17.1
Mallee	Western Mallee	13.7	11.1	15.7	14.9	8.7	7.4	5.4	4.5
	Eastern Mallee	12.6	12.4	12.9	13.9	9.4	9.6	5.3	5.7
Swan Coastal Plain	Perth	18.4	20.4	14.8	18.0	20.7	22.8	22.0	22.5
	Dandaragan Plateau	15.5	12.8	15.6	11.9	21.2	16.6	19.2	16.0
Warren	Warren	12.2	14.4	11.2	14.1	8.7	11.7	8.5	11.2
Yalgoo	Edel	0.4	0.0	0.4	0.0	0.0	0.0	0.3	0.0
	Tallering	0.9	0.0	0.9	0.0	0.1	0.0	0.6	0.0

6.3.1.2 Forage availability – future

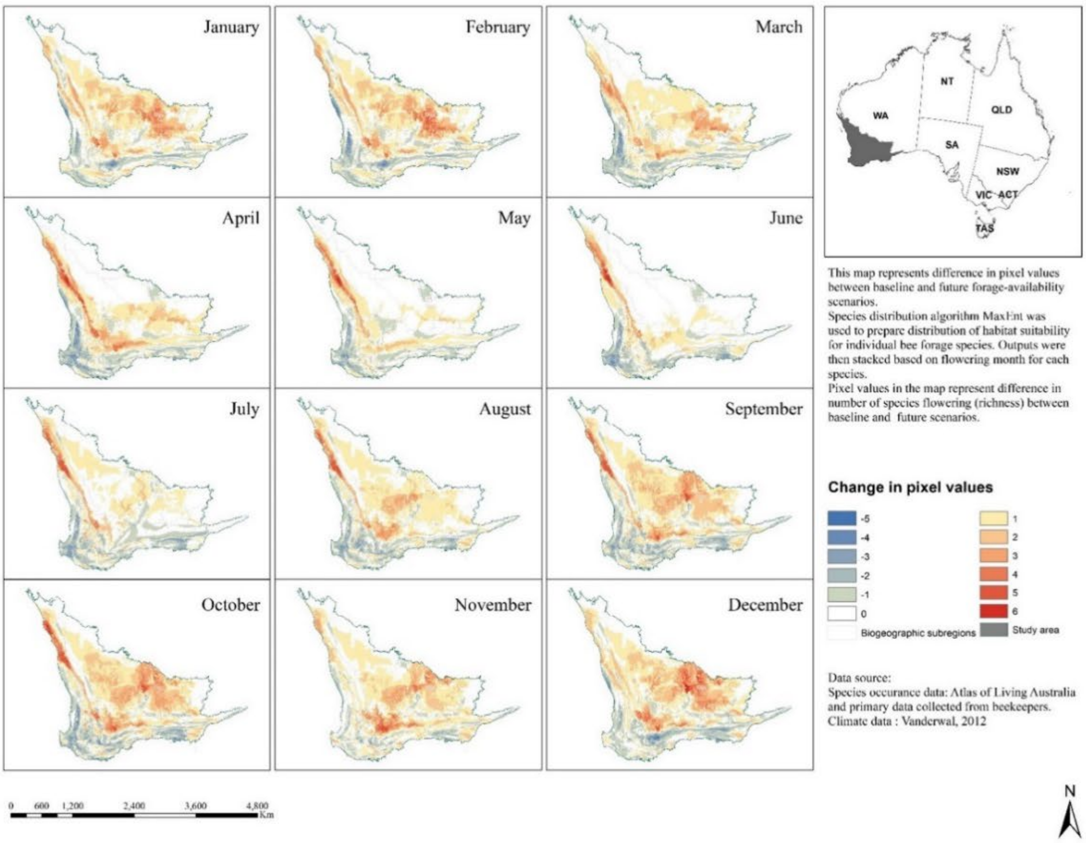
The future scenario shows a similar regional distribution as the baseline scenario of forage availability, with higher values of species richness evident in Swan Coastal Plain and Esperance Plains (Table 8) in all months (Appendix 5, Figure 5.3). Despite a similar spatial distribution observed at the seasonal level between baseline and future scenarios, there is an apparent shift in species richness values. Comparing future forage availability to the baseline, an increase across all seasons is observed in the biogeographic subregions of Perth, Warren, Northern and Southern

Jarrah Forest. Conversely, average species richness values decrease for Merredin, Katanning, Southern Cross, Eastern Goldfield, Geraldton Hills, Lesueur Sandplain, Western Mallee, and Dandaragan Plateau during all seasons. This analysis highlights Swan Coastal Plain and Esperance Plains as the most species-rich regions for forage availability, where statistically significant clusters of high species richness are observed across the seasons (Appendix 5, Figure 5.4).

6.3.1.3 Change in forage availability

The difference in forage availability between baseline and our future scenario suggests significant variability in species richness between the two time periods (Figure 19.A). The greatest change in richness is observed during the summer months (December – February). When comparing the future scenario to baseline forage availability, an 18.5% increase in species richness was observed, with 52.7% of the research area exhibiting a decline in species richness. The variability in species richness declines in autumn (March – May) in the future scenario when compared to the baseline. The smallest changes in species richness extent (16.9% of the total forage area) were observed in June (i.e., the start of winter) before increasing again during early spring (September – October). Premium species are available for less than 8% of the total study area and found primarily within the biogeographic subregions of Jarrah Forest, Swan Coastal Plain and Warren. The difference in the availability of premium species during January to March (i.e., peak flowering season for Marri) for the future scenario versus baseline, suggests a decreasing availability of Marri (12.3% of the Marri distribution). The results for zonal statistics are provided in Appendix 5, Table 5.3, which suggest a loss of Marri in Swan Coastal Plain, Jarrah Forest and Geraldton Sandplains, with an increase in the distribution of Marri in Recherche (Blue colour in figure 19A). Similarly, the results representing the peak flowering window for Jarrah (September – November) suggested a decline in 18.9 % of the total area for Jarrah, specifically in biogeographic regions of Jarrah Forest and Swan Coastal Plains (red colour in Figure 19B).

A



B

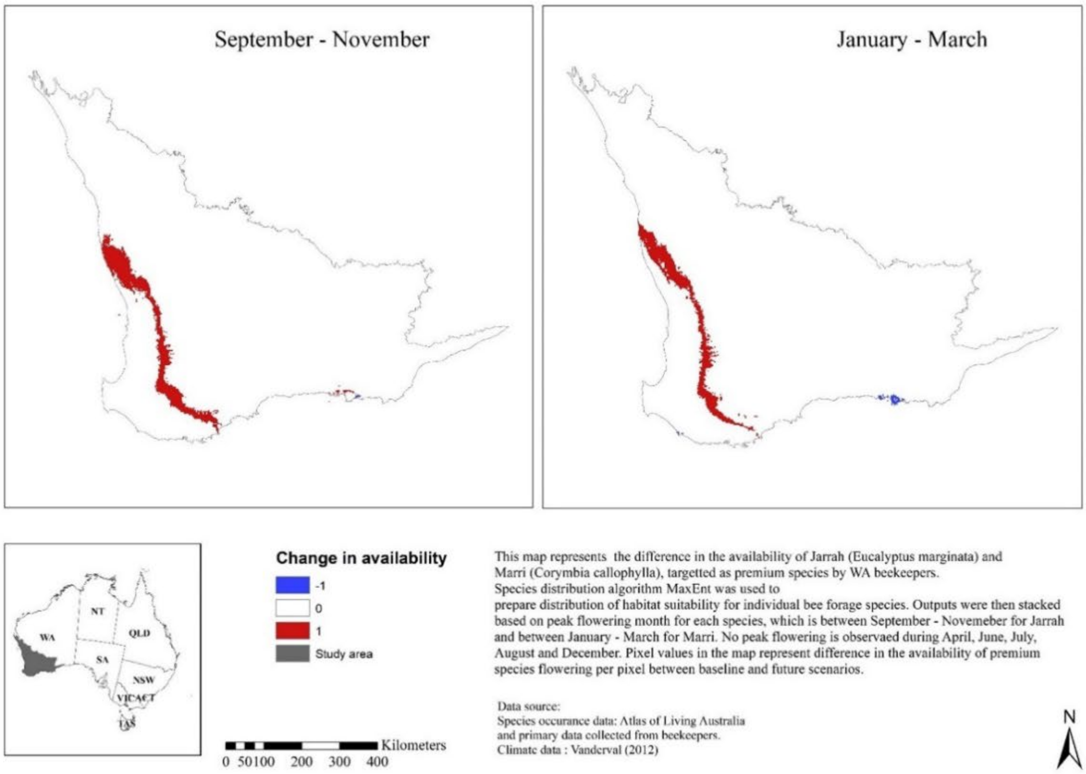


Figure 19: Forage availability calculated as difference in pixel values between baseline and future forage availability scenarios, where pixel values represent the difference in (a) number of species flowering per pixel (species richness) and (b) change in number of premium species flowering in a pixel. Zero values represents no observed change, positive values (red) represent a decrease and, negative values (blue) represent an increase in number of target forage species flowering within the pixel.

The forage availability patterns observed in this analysis suggest a southern and eastward shift in resource availability into the future, with our interpretations assuming a universal dispersal scenario where future distribution mirrors the future spatial extent of its suitable environmental envelope (Yates et al., 2010). The changes in distribution for the key bee forage species included in *B-Agent* also support similarly reported spatial range shifts of individual species targeted for beekeeping, as identified for Eucalyptus spp. (Gonzalez-Orozco et al., 2016; Hamer et al., 2015) and Banksia spp. (Yates et al., 2010).

6.3.2 Patterns in beehive migration

The results presented for the beehive migration ABM successfully reproduced the expected patterns in travel distance, hive site use, and maximum range of hive migration frequency. We acknowledge the uncertainty in forage availability inputs relative to climate projections and therefore tested the ABM using S-SDM prepared using bioclimate variables representing a high emission (RCP8.5) climate scenario as well. The comparison of SDM outputs (Table 5.4 and 5.5) for individual species and associated ABM outputs (i.e., patterns in travel distance (Table 5.6), frequency of beehive migration (Table 5.7), and shift in harvested forage locations (Table 5.8)) are included in Appendix 5.

6.3.2.1 Patterns in distance travelled by beekeepers

The analysis of annual distances travelled by commercial and semi-commercial beekeepers shows significant variation during the multiple *B-Agent* model runs. While the distance travelled per month for semi-commercial beekeepers indicated minimal changes between the baseline and future scenarios, commercial beekeepers experienced an increase in travel during all months in the moderate emissions future scenario (Figure 20A and B). In the case of semi-commercial beekeepers, a small reduction was observed in annual travel distances between the baseline and moderate emissions future scenario (-15.5 km). Conversely, for commercial beekeepers, an increase in travel distance of 323.6 km was observed between the two scenarios (Figure 20B).

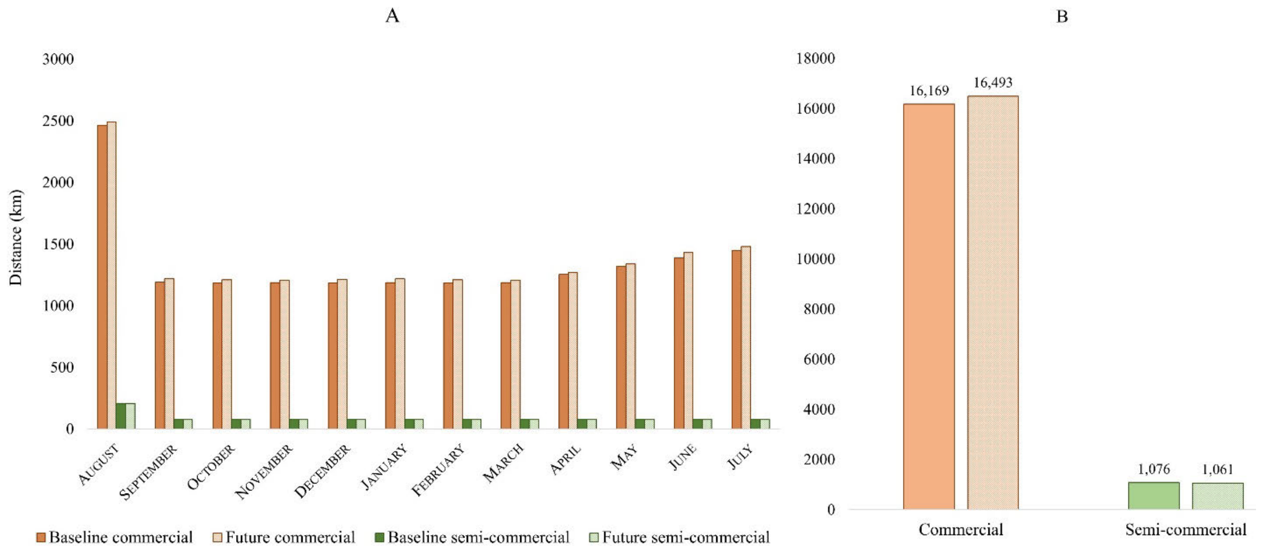


Figure 20: A) Average monthly distance travelled by commercial and semi-commercial beekeepers for beehive migration under baseline and future forage availability scenarios; and B) Annual average distance travelled by commercial and semi-commercial beekeepers for baseline and future forage availability scenarios (mean of total_distance_travelled across 100 model runs for each scenario).

A beekeeper's preference for forage sites closer to home over distant sites (Galbraith et al., 2017) is a significant contributor to the variable travel patterns explained here. Similarly, the number of loads owned by a beekeeper and a beekeeper's initial location (*my_home*) affects the travel patterns observed. Beekeepers with a similar number of loads show comparable patterns, for example, smaller difference were observed in annual travel between commercial beekeeper with five loads (905.9 km) and a semi-commercial beekeeper with four loads (763.4 km). The observed peak in monthly travel in the future scenario during autumn is likely due to commercial beekeepers returning closer to home for winter from longer distance travelled during previous months (Gordon et al., 2014). The emergent patterns through the hive migration ABM simulation runs suggest that the mean annual distance travelled for commercial beekeepers is always higher than semi-commercial beekeepers, supporting one of the known patterns for the WA beekeeping industry, as identified in Section 6.2.3. Testing the ABM with forage availability inputs prepared using the high emission (RCP8.5) climate scenario (Table 5.6 Appendix 5) also shows higher travel distance for the commercial beekeepers (16008.1 km) as compared to the semi-commercial beekeepers (1036.5 km).

6.3.2.2 Patterns in frequency of beehive migration

The frequency of beehive migration indicates the number of times beekeeper agents migrate their loads (i.e., mean *move_count* of *my_loads* of beekeeper agents). The average value of the frequency of hive migration (*shifting*) remains consistent for baseline and future scenarios. Modelled patterns for the maximum hive migration frequency remained within the maximum range observed in WA (i.e., six times per year). The minimum value for *shifting* was zero in both scenarios, with those beekeepers recording zero *shifting* all semi-commercial, with only one load. Spatial-temporal availability of forage resources triggers behaviour patterns for migratory beekeepers (Albayrak et al., 2021). In addition, the distance travelled contributes to variable conditions for migratory colonies (Alger et al., 2018). Movement decisions in an ABM rely on the internal state and the local environment of an individual agent (DeAngelis & Diaz, 2019). According to the rules implemented in the hive migration ABM, one patch can only serve one load, and beekeepers will only move loads if the forage at the load location is reduced to zero. Therefore, it is possible if a beekeeper with one load is initialized from a postcode that has consistent forage availability (e.g., Muchea). These results further highlight the importance of locations with year round forage availability.

6.3.2.3 Patterns in forage site use

Forage site use is found to vary between baseline and future scenarios. In the baseline scenario, modelled harvested locations were concentrated in the western regions of the study area, which reflects decisions by beekeeper agents to prioritise using harvest sites with premium species flowering in the same region (e.g., Figure 19B - Northern Jarrah Forest and Southern Jarrah Forest biogeographic subregions). In the future scenario, an increase in harvested cells within Northern Jarrah Forest also supports a preference by beekeeper agents to harvest premium species. An increase in the number of cells harvested in southern regions (Warren and Fitzgerald subregions) and eastern regions (Eastern Mallee and Eastern Goldfields subregions) was observed in the future scenario, where an increase in species richness was found (Figure 19A).

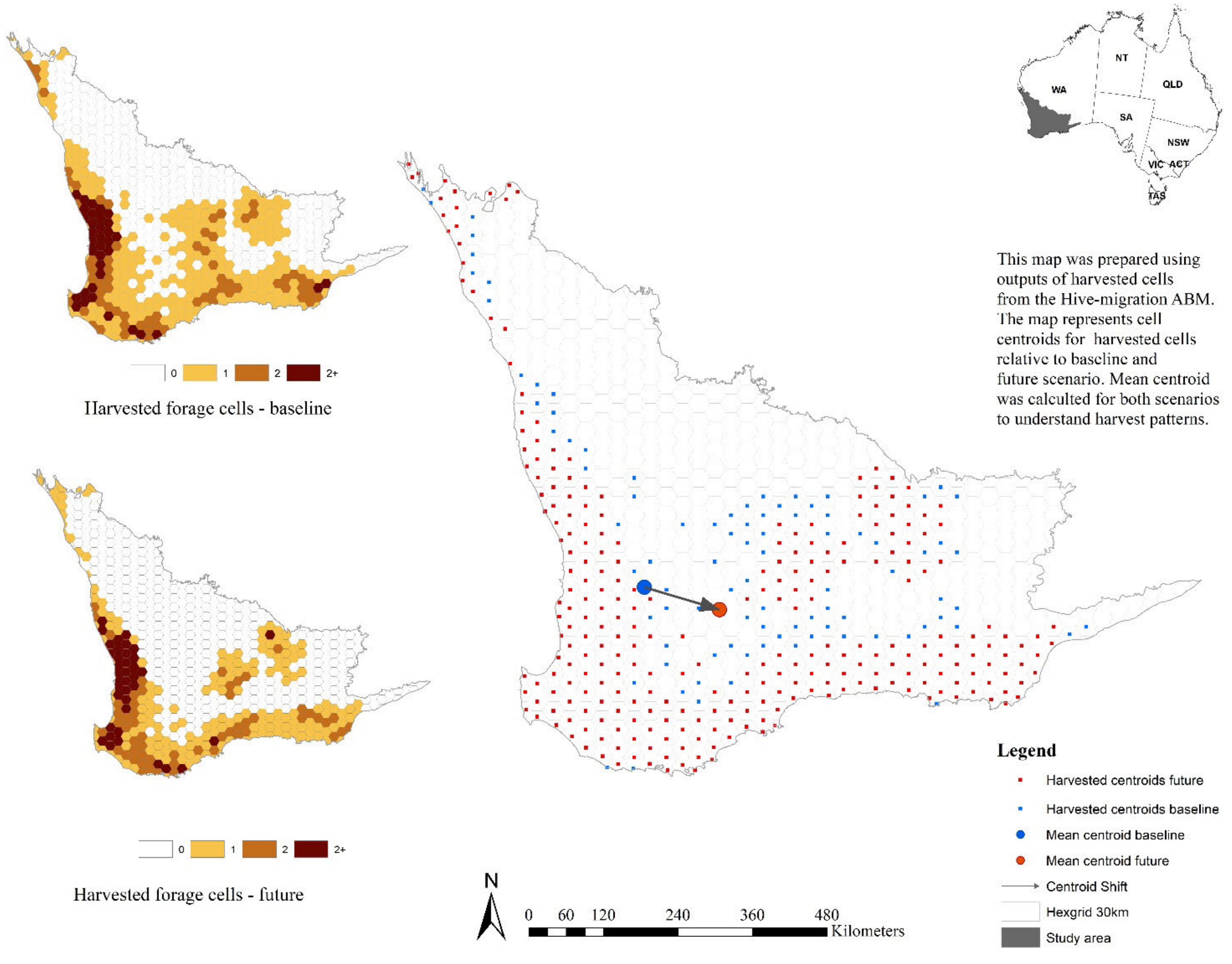


Figure 21: Patterns in forage site use between baseline and future forage availability. Maps of harvested forage cells represents raster outputs of harvest_count aggregated using 30 km hexgrid, where darker values represent a higher harvest_count in aggregated cells. Small squares represent centroids for harvested grids, where the blue colour is used for baseline and red for future scenario.

The results of mean coordinates of aggregated harvest areas comparing baseline and future scenarios, indicates a shift of 126.4 km eastward (Figure 21) in the moderate emission climate scenario. The results presented here support observations in Patel et al. (2020) which suggest beekeepers are already shifting forage usage patterns to access more forage sites located further inland. When testing the ABM with the high emission climate scenario, an eastward shift in harvested locations was also observed with a mean distance of 77.2 km (Table 5.8, Appendix 5).

6.3.3 ABM output validation

The modelled mean travel distance was compared with the distance calculated based on the forage site sequence used by beekeepers across a single year (i.e., spring 2016 – 2017) using a paired two sampled t-test. The sample size (N), mean (M) and standard deviation (SD) of travel distance are provided in Table 9.

Table 9: Comparison of mean travel distance obtained from the hive migration ABM (based on 14 beekeepers) and travel distance calculated between the sequences of apiary sites used by beekeepers.

Beekeeper Type	**Modelled distance (km)**			**Distance calculated from data (km)**		
	M	**SD**	**N**	**M**	**SD**	**N**
Commercial	5848.0	3171.4	7	8441.4	3729.9	7
Semi-commercial	1092.9	1283.1	7	1001.9	1156.2	7

The results of the two sampled t-test and *p* values for commercial ($p = 0.13$) and semi-commercial beekeepers ($p = 0.14$) suggest that there is no statistically significant difference between the modelled mean travel distance and the mean distance calculated from the data collected from beekeepers.

6.3.4 Management implications, limitations, and future directions

B-Agent was designed to inform management decisions to ensure sustainability of the WA beekeeping SES. Changes in land use, climate, and/or environmental management decisions can substantially affect the availability of quality forage sites accessed by beekeepers, resulting in changing mobility patterns (Ausseil et al., 2018; Castellanos-Potenciano et al., 2017; Otto et al., 2016). The results of our *B-Agent* analysis provide an improved understanding of the interconnectivities associated with forage availability and beehive migration patterns by incorporating human decision-making. This has the following management implications:

1. Protecting or planting bee forage resources are essential to support managed bee pollinators and to ensure sustained honey production. *B-Agent* provides identification of current important forage regions and likely future shifts in the spatial distribution of bee forage species. This knowledge will help develop spatially targeted habitat restoration initiatives to advance bee conservation (Tonietto & Larkin, 2018) while positively contributing to the resilience of beekeeping systems. Such informed land management decision-making can have a positive impact on the resilience of beekeeping. For example, Afforestation using important melliferous (honey producing) species has compensated the loss of forage resources for beekeepers in Uruguay (Malkamäki et al., 2016).

2. Beekeeping behaviours are driven by forage availability (Albayrak et al., 2021). *B-Agent* represents beekeeping behaviour through incorporating an empirical decision-making model for beekeepers. The example explaining interconnectivities between forage variability relative to future climate and beekeeping behaviour is presented for WA in this paper. *B-Agent* can be used to produce similar examples to understand change in behavioural patterns of migratory beekeepers relative to land management dynamics or policy decisions. For example, questions such as how beekeeping behaviour patterns may be impacted by the proposed Forest

Management Plan (Conservation Commission of Western Australia, 2013) amendments coming into effect for 2024-33 in WA that aim to protect native forests including karri, jarrah and wandoo forests (Morton, 2021); these are some of the most important regions for beekeepers.

B-Agent highlights that beekeepers' migratory patterns including travel distance and frequency of hive migration will change in the future with more use of inland (remote regions) forage sites. Although the variation in travel distance seems relatively small in numbers, it may have a significant social and economic impact on beekeepers. In the first instance, an increase in travel distance will increase associated fuel cost and importantly *B-Agent* does not include additional trips made to selected forage site (e.g., checking forage condition at the site before hive placements and/or hive performance and health after hives have been placed on a site). With such multiple trips to and from the forage site, a slight increase in the distance can have a significant impact on the economic outcome of beekeepers. In addition, increasing the use of inland (i.e., remote locations) forage sites is not only fuel-intensive but can also lead to exposure to extreme site conditions and social isolation for beekeepers (Phillips, 2014). Here, it is important to note that the resource layer used in *B-Agent* represents the spatial distribution of flowering species richness using an aggregation of thirty species. This may hide the nuances of a larger shift in specific individual species. In addition, climate induced phenologic changes and interconnectivities between some environmental stresses (e.g., climate change and fire (Abram et al., 2021)) may also affect individual forage species and flowering species richness which should be considered in future research using *B-Agent.*

B-Agent, although built using WA specific data, was designed so that the spatially explicit forage environment can be calibrated to other locations using local forage species of different application sites. The transferability of *B-Agent* for use in other locations will benefit the sustainability of multiple beekeeping SESs; the selection of forage sites by beekeepers is modelled using forage and proximity characteristics which are universally important for migratory beekeeping systems around the world (Albayrak et al., 2021; Pilati & Fontana, 2018). *B-Agent* also has the potential to integrate more nuanced data, for example, enhanced spatial accuracy could be achieved by incorporating spatial network analysis and routing algorithms to model migration patterns using specific transportation routes.

6.4 Conclusion

B-Agent provides a hybrid model to assess the social-ecological interconnectivities associated with beehive migration processes. The methods presented in this paper contribute to an advancing knowledge regarding hive migration decisions not previously included in ABMs of beekeeping SESs. For application in WA, *B-Agent* has enabled the identification of the spatial extent of species composition important for beekeeping, with 30 key bee forage species noted. The seasonal and monthly changes in spatial distributions of these key bee forage species, along with composite species richness, have been visualised for baseline and future scenarios. Beehive migration patterns in WA have been modelled using *B-Agent* with future forage availability suggesting a shift in hive site use (in an ESE direction), in the relative distance travelled by commercial beekeepers, and an increase in the frequency of beehive migration. The known structurally interconnected patterns associated with the impacts of climate change on the beekeeping SES have been supported by the results. Based on these findings, land restoration and reforestation initiatives should consider using *B-Agent* to inform planting decisions according to the habitat suitability of forage species. With the projected change in future forage availability, current decision-making strategies for beekeepers may also need to change in order to maintain sustainable production. *B-Agent* presents the complexities associated with beehive migration process as a pragmatic modelling tool for multiple users, including beekeepers and decision-makers, to assess the impacts of various pressures on the beekeeping SES and better inform management decisions to achieve the long-term sustainability of beekeeping systems.

Chapter 7. General Discussion and Conclusions

7.1 Summary of research findings

In recent decades, beekeeping has gained recognition for its contribution to sustainable development. Bee-human systems and the interdependencies they represent contribute to a range of benefits for both human and ecological systems. However, complex natural and anthropogenic pressures are impacting bee-human systems and their ability to support sustainable development. This requires a better understanding of the system's key components, interconnections, and interactions to assess the impact of system pressures and inform resource management decisions to ensure the sustainability of beekeeping contributions. A social-ecological systems framework (SESF; McGinnis & Ostrom, 2014; Ostrom, 2009), which presents a hierarchy of social-ecological concepts nested in multiple tiers, provides a lens through which the key components and interconnections of the bee-human relationship can be examined. The SESF was designed for application to the management of common-pool resources, in which people are accountable for sustainable extraction and maintenance of natural resources (McGinnis & Ostrom, 2014; Rodela et al., 2019). The SESF is widely applied to resource sectors such as forestry, agriculture, and fisheries, due to the specificity of some SES concepts to a particular sector (e.g., sea-bed tracts as a lower tier within benthic small-scale fisheries (Basurto et al., 2013) or transformation systems and products as the first tier concept (Marshall, 2015)), the development of sector-specific SESFs that account for local interactions unique to specific sectors remains an active research area (Partelow, 2018).

SESs represent complex adaptive systems (Levin et al., 2013; Preiser et al., 2018), in which individual entities (e.g., actors presented as agents) behave according to a simple set of rules resulting in emergent behaviour at the systems level. Modelling complex SES interactions is challenging and requires integrating multiple modelling approaches to represent multiple SES entities and their complex interactions (Elsawah et al., 2020). Agent-based modelling (ABM) is widely being used for SES modelling for its ability to represent an individual agent's behaviour and mobility, understand system-level emergent properties, and account for the human decision-making processes (Elsawah et al., 2015; Kelly et al., 2013; Schlüter et al., 2019; Zvoleff & An, 2014). SESF captures a representation of an agent-based system through expressing complex SES behaviour (e.g., agent-based SESF capturing complex behaviour in fisheries systems (Cenek & Franklin, 2017). While recent advances in the application of systems thinking and integrated modelling have attempted to address the multifaceted livelihood that is beekeeping, the majority of these approaches have not considered migratory beekeeping, specifically the decision-making process that governs how and when beekeepers move their hives from one location to another. Beehive migration is an explicitly spatial process. This thesis presents the first model that accounts for the spatial interactions of beekeepers with forage landscapes and the decision-making processes that governs those interactions.

The research presented here fills a critical knowledge gap around the systemic understanding and modelling of bee-human relationships in order to sustain system contributions to humans and the environment. The overarching objective was to examine the bee-human relationship through the lens of SES, identify key interconnectivities within the system, and develop a model representing SES interconnectivity to address the impacts of natural and anthropogenic pressures at the system level. This overarching objective was addressed through four principal objectives:

i) Develop an understanding of the interconnections between bees and people, in the context of the Sustainable Development Goals (SDGs),
ii) Through the lens of social-ecological systems thinking, characterise the elements, patterns, processes, and feedbacks of a commercial honey production system as well as the pressures acting on the system,

iii) Identify spatial patterns of bee forage availability under future climate scenarios in a spatially bounded region experiencing the effects of climate change

iv) Develop an integrated model representing the beehive migration process to examine how changes in forage availability will affect spatial patterns of beehive migration.

Each of these objectives was achieved through answering one or more research questions, the findings of which serve as the basis for the four results-focussed chapters of this thesis (Chapters 3, 4, 5 and 6). Together, the thesis presents an innovative body of research that contributes to the broader knowledge of bee-human systems (i.e., the bee-human relationship and its contribution to achieving sustainable development goals), advances the existing social-ecological systems framework (i.e., developing the sector-specific SESF for migratory commercial beekeeping), and develops a novel integrated modelling framework, *B-Agent,* to simulate beehive migration process in order to examine the impacts of SES pressures (i.e., the impacts of climate change on structurally interconnected beekeeping SES).

The methodology employed in this thesis draws upon both qualitative and quantitative techniques, each of which present their own challenges, yet together, contributed to a robust research design. The remainder of this chapter is structured as follows: first, I highlight the methodological challenges encountered during the research journey; second, I provide a discussion of research findings and key contributions, and finally, I acknowledge the limits of the research and synthesise recommendations for future work.

7.2 Methodological challenges

In this thesis, a combination of methods were used including stakeholder engagement, species distribution modelling (SDM) and agent-based modelling (ABM). Prior to embarking on a PhD, my primary expertise was in the use of geographic information systems (GIS) as applied to a range of disciplines however, qualitative research, involving multiple individual and group stakeholder engagement, and quantitative systems modelling, was new to me. My research journey began with a steep learning curve that was fraught with methodological challenges influencing the overall research design. This section discusses these challenges and the resulting outcomes of this research.

7.2.1 Challenges and opportunities presented by stakeholder engagement

In this research, I presented the first application of the SESF by Ostrom (2009) and furthered by McGinnis and Ostrom (2014) for understanding beekeeping as a social-ecological system through identifying key components and their interactions within the system. The SESF provides a structure for describing a hierarchy of multitier interacting components that represent core SES concepts. Being the first application of the SESF to the beekeeping system, I found limited information on the topic within both published and unpublished literature, which impacted the identification of system components and their interactions and required the collection of in-depth local knowledge from key stakeholders to identify, verify and validate the local beekeeping SES presented in Chapter 4.

Identifying and recruiting stakeholders was challenging and required iterative interactions with industry groups to garner support for the research. First, by presenting my ideas at beekeeping conferences, a network of potential stakeholders was developed to inform the work. Stakeholders included commercial beekeepers, government officials, industry experts and academics. Importantly, the concepts of resources, actors and governance were the concepts understood by most stakeholders, but lower tiered components of an SES were both complex and foreign to most. I also had a good discussion about the six core SES concepts (i.e., RS, RU, GS, A, I and O as identified earlier in this section) of the beekeeping SES with intergenerational and highly experienced beekeepers, who found this research very interesting and timely in addressing their resource-related issues. To recruit study participants, the Bee Industry Council of Western Australia (BICWA) placed flyers advertising my research on their website which facilitated further interactions with industry stakeholders through both formal (e.g., regular meetings of beekeeping associations) and informal meetings (e.g., volunteering during annual farm shows) to discuss the research and potential implication for the industry.

Commercial beekeeping was a very small industry in 2017 with a total of 127 beekeepers with 50 or more hives. This relatively small industry was further divided into smaller groups, and each preferred to keep their beekeeping knowledge to themselves. Individual beehive migration patterns, particularly spatial-temporal information concerning apiary site use and forage species at specific locations, was crucial for the development of a spatially explicit model representing beehive migration. However, maintaining the secrecy of this information is often what provides competitive advantage, particularly as most of the honey production in WA comes from a finite supply of native floral resources occurring in the southwest corner of the state. Obtaining this information required ongoing interaction with beekeepers to establish trust and prove my ability to protect this commercially sensitive information.

Through regular interaction with the industry, I was able to gain the trust of several older and highly respected beekeepers. Their interest, and my persistence, encouraged more beekeepers to participate in the research. Further, although recruiting government representatives was comparatively straightforward, the collection of confidential spatial datasets (e.g., apiary permit coordinates) from government departments was challenging. Because the research was developed with funding support from the Cooperative Research Centre for Honeybee Products (CRCHBP), the organisation was able to help facilitate the acquisition of confidential spatial information (e.g., apiary permit owners and their locations) from government departments across the state.

7.2.2 Integrating methods that account for intertwined systems

By developing a systematic understanding of beekeeping, I identified complex intertwining between forage landscapes and beehive migration. I also understood that pressures on forage resources affected other interconnected system components. For example, burning of forage resources impacts forage availability, and therefore influences beekeepers' decisions to use (or not use) fire-affected sites. Similarly, altered rainfall patterns have led to increased flowering availability in eastern portions of the state, which is further reflected in the increased use of inland forage sites (see Chapter 4; Patel et al. (2020)). Once I had established a strong argument for interconnectedness based on qualitative information, the next step was to develop a quantitative evidence base, which can help decision makers to better understand these interconnections (Chapter 4) for improved land management decision making.

Here, I selected an ABM approach to model SES interconnections within the beekeeping systems due to capacity for incorporating forage landscapes, beekeepers' decision-making and beehive mobility within a single modelling framework. Being a novice at this type of programming, I started learning ABM using NetLogo, which is simple and easy for building medium to large scale ABMs (Abar et al., 2017). Combining qualitative and quantitative data, and representing human decision-making are some of the grand challenges in SES modelling, which require novel multi-method methodologies and tools (Elsawah et al., 2020). I encountered these challenges (i.e., combining qualitative and quantitative data and incorporating human decision-making) in this research.

The focus of beehive migration is to utilize a sequences of forage sites for profitable honey production (Pilati & Prestamburgo, 2016). In previously developed migration related ABMs, an individual agent's decision to migrate to another location primarily follows utility maximization thinking, in which agents decide to migrate to a new location based on the potential attractiveness of the location to maximise an expected utility (Klabunde & Willekens, 2016). As such, the potential attractiveness (PA) of an apiary site is the honey production potential (HPP) for a location, which requires knowing each site's target species, the number of plants available as forage, the total number of flowers per plant, the average amount of sugar per flower, and the length of flowering per species (Khisamov et al., 2018). Calculating HPP for each apiary site may have been possible in the case of a small number of sites however, calculating HPP was not feasible due to the high diversity of forage species used by apiarists in WA and the size of the forage landscape.

Alternatively, PA can be calculated based on historic honey production data for a site. With this in mind, I embarked on a participatory mapping data collection exercise with individual beekeepers, using the locations of their apiary sites to gather information for each of the following: target forage species; time and duration hives occupied the site; the number of hives placed at each location; and total honey production. This idea soon presented its own challenges as most participants did not maintain records of their migration patterns or production by site; records were often collected as honey produced at multiple sites with no apparent way of disaggregation. For example, some participants provided invaluable support by sharing their historical diary records of beehive migration and shared their time in spatialization of some of these records (Figure 22). However, converting these records into a format that could be used in the model, required a significant amount of time and involvement from their busy schedules, potentially exceeding the research duration limit. In addition, historical migration and production data was also available for only three out of 29 participants, which was not sufficient to understand migration decision making processes for the whole industry. Therefore, I decided not to continue with spatialising all diary records.

Figure 22: Intergenerational beekeepers helping to spatialise historical beehive migration records.

However, I uncovered historical records for one participant, which included coordinate level apiary site information, an ID for each hive load (i.e., a collection of beehives (about 90 – 100 beehives) that beekeepers transport together) and information linking each load to the bulk honey containers supplied to local packagers. Based on the container ID, honey volume per container was collected from the packer which could then be disaggregated to the apiary site and associated with the particular target species at each location. Figure 23 provides an illustration of this process.

The participant found the whole exercise very useful and updated their system of record keeping (i.e., recording production per apiary site), which can be very useful for future modelling of honey production or similar research. However, being the only comprehensive historical record, this information could not represent the WA beekeeping system as a whole, and therefore, could not be used in ABM.

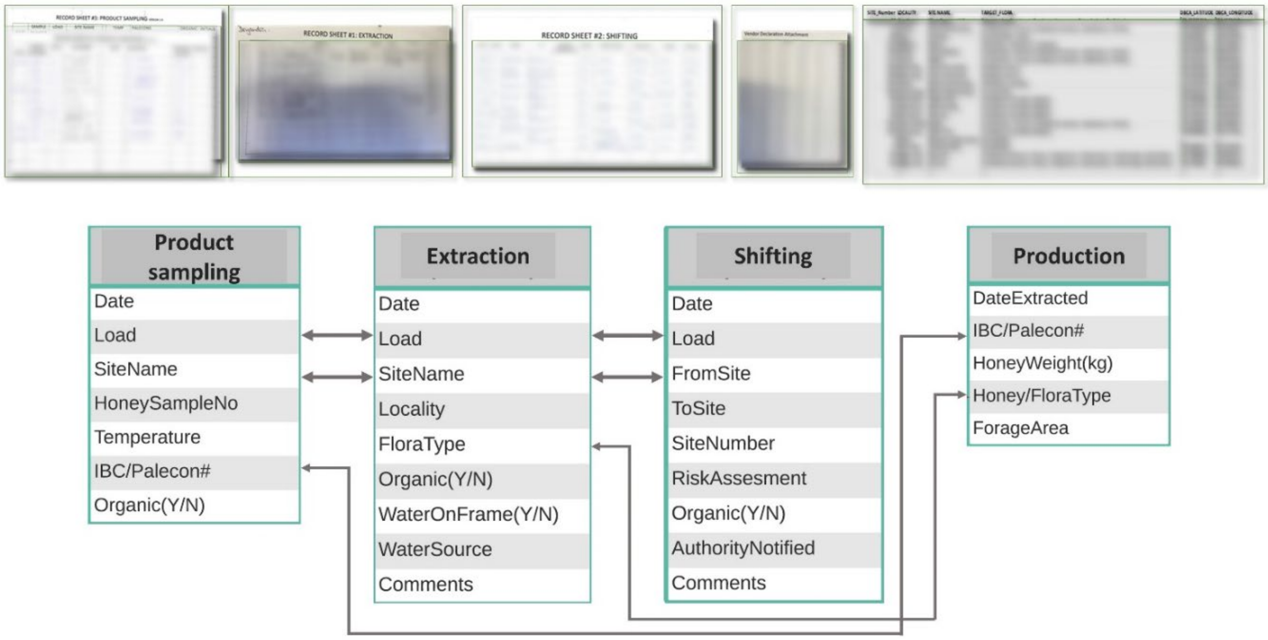


Figure 23: Example of historical migration data collected from beekeepers and links to forage site coordinates, target species, number of hives and bulk honey production from a collection of forage sites. Here, readability of apiarist data is deliberately reduced to maintain data confidentiality.

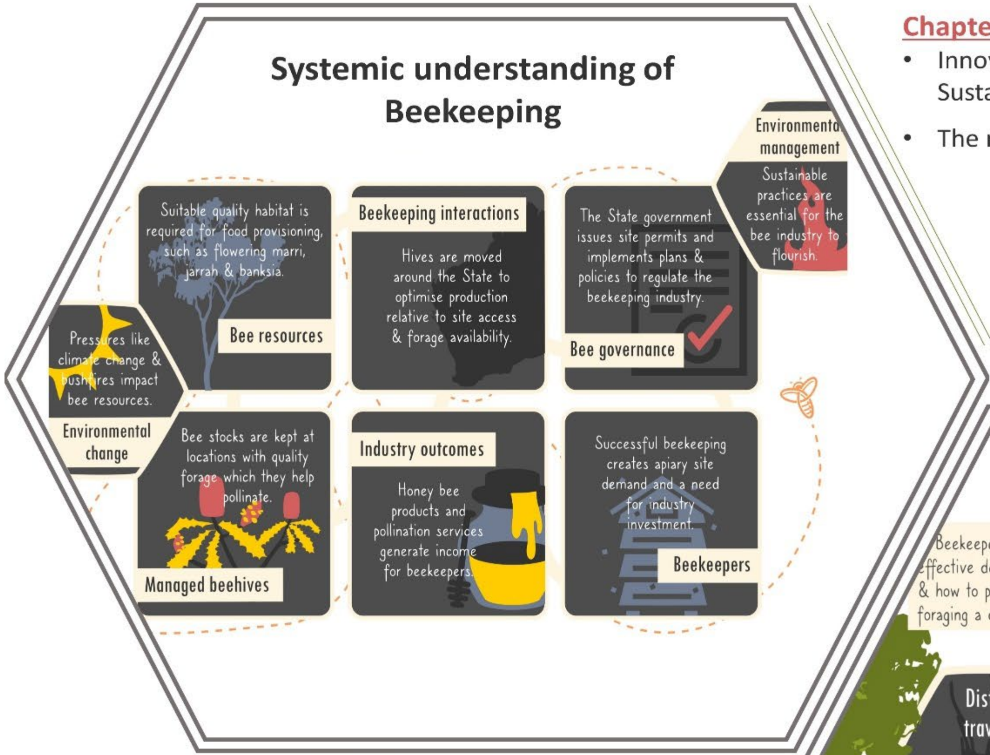
To this end, I was required to develop a novel approach for modelling beehive migration decision making which can be used for similar modelling initiatives in data-poor systems. To overcome this challenge, I reengaged with qualitative data gathered from stakeholders concerning key forage species targeted and the factors that contribute to selecting forage sites based on flora availability and associated flowering times. I also realised that restricting beekeeper's movement to only apiary permit sites was not entirely representative of the real beekeeping system as apiarists use a mix of private and public forage sites, as well as sites with one another. Therefore, in the end, I decided to model the forage environment as a common-pool resource (i.e., assuming each beekeeper has access to all available forage site) where species distribution modelling (SDM) was used to predict the current and future distributions of target forage using species presence-only data (Chapter 5).

After successfully creating forage availability scenarios and modelling beekeepers' movements based on decision rules adapted from stakeholder data, the real challenge was incorporating the movement of hive loads into the modelling framework. In migratory beekeeping systems, migratory entities are described as loads of hives (approximately 100 hives), but the decision-making entity is the beekeeper. Beekeepers prefer to move their loads in a cluster so that the travel cost does not outweigh the production benefits from each migration. In this case, the local environment for each load is different for each model time step (i.e., one time step is one month). The migratory entity (i.e., loads of beehives) acts according to the state of the local resource environment therefore, the decision-making should be executed by migratory entities. Coding this relationship in an ABM was challenging, as seemingly simple decision rules followed by beekeepers were found to be more complex when the decision to move a load based on the forage-availability of a site was incorporated into the model.

I also invested significant time and effort to include beekeeper travel based on WA's road network. Programmatically, this was extremely challenging particularly when incorporating load movement. In the end, I conceded to modelling hive movement based on Euclidean distances only, highlighting this omission as a limitation of the research. Overall, these challenges provided a valuable learning opportunity which supported my growth as a researcher, resulting in the development of a novel application to addressing SES pressures on migratory beekeeping systems that has made a substantial contribution to the conceptual and operational knowledge of social-ecological systems.

7.3 Research findings and contribution

This thesis presents significant original contributions to the theoretical and methodological knowledge of integrated bee-human systems. This was the first study to present a holistic view of bees and humans as an interconnected system, a perspective that was advocated as necessary to address sustainability challenges (Kleijn et al., 2018; Rupprecht et al., 2020; Saunders et al., 2018). The findings and contributions of this research are presented in Figure 24, which can be encapsulated into two major aspects: i) Systems understanding and ii) Integrated modelling.

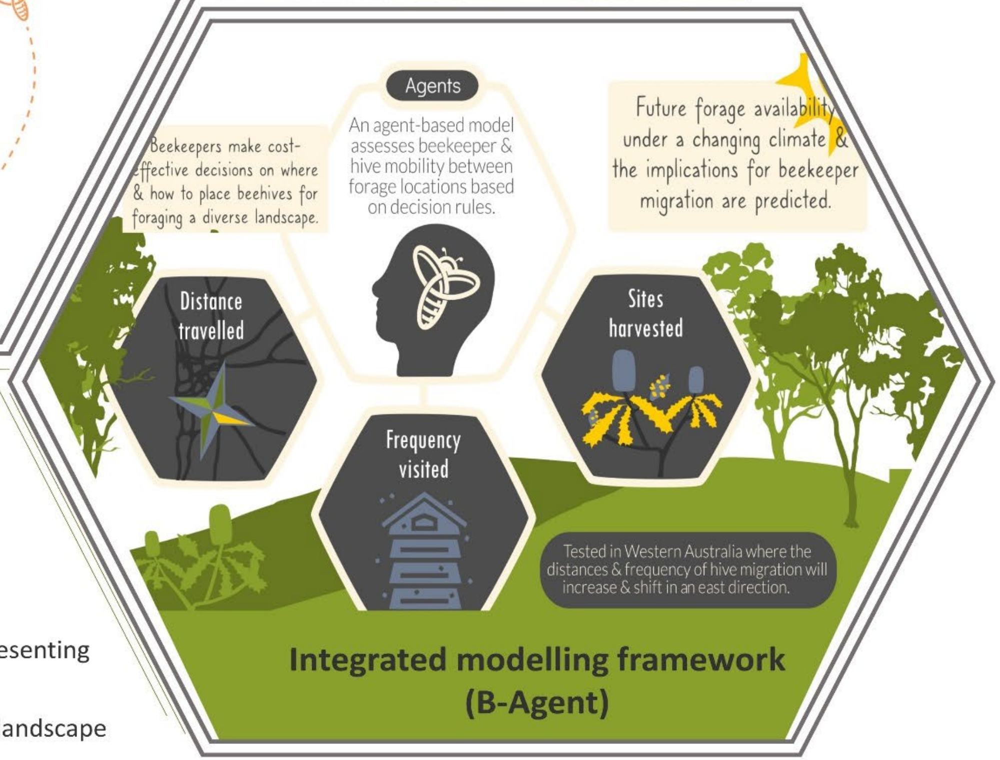


Chapter 3

- Innovative assessment of Bees' contribution to achieving 15 out of 17 Sustainable development Goals (SDGs) was presented
- The need for understanding the bee-human system is emphasized

Chapter 4

- First characterization of beekeeping as a social-ecological system (SES)
- Development of beekeeping sector-specific application of Social-ecological Systems Framework (SESF) with the identification of 168 SESF variables and key SES interconnectivities



Chapter 5

- Change in the spatial distribution of key bee forage species relative to future climate estimated for 30 key bee forage species
- Novel application of Species Distribution Model (SDM) for developing beekeeping forage-availability scenarios

Chapter 6

- Integrated spatial modelling framework (B-Agent) representing migratory beekeeping decisions
- Novel approach to integrating dynamics of bee forage landscape and beekeepers' hive migration decisions

Figure 24: Theoretical and empirical contributions of the thesis, with each core research chapter making a specific contribution to the advancement of conceptual and operational knowledge of the social-ecological system.

7.3.1 Systemic understanding

The research in this thesis makes several important contributions to ongoing discussions around the relationship between bees and society. Thus far, scholars have explored the bee-human relationship primarily using the livelihoods or ecosystem cascade framework (Matias et al., 2017). While the potential of an in-depth understanding of this interdependent bee-human relationship to inform sustainable practices is increasingly being recognised, knowledge is limited on the systemic understanding of this relationship. In addition, despite the potential for transdisciplinary contributions, viewpoints from single disciplinary domains (primarily ecology and anthropology) dominate the existing research on bee-human relationships (Matias et al., 2017). The first two objectives of this thesis investigate a series of research questions to find information on developing a systemic understanding around bee-human systems.

First, the research delves into the current body of evidence to establish the interconnections between bees and people (Objective 1), specifically, investigating how bees and people are connected and what contributions these connections make in achieving sustainable development. This investigation resulted in an innovative assessment of the critical contribution of bees toward the United Nations Sustainable Development Goals (SDGs), whereby the potential contribution to at least 30 targets across 15 of the 17 SDGs was identified (Chapter 3). Chapter 3 significantly contributes to the theoretical understanding of bee-human systems by emphasising the contribution of the bee-human relationship beyond the disciplinary domains identified above and proposes eight overarching thematic priority areas as a foundation for a research agenda that calls for a systematic exploration of bee-human relationships.

Towards a systematic exploration of bee-human relationships, a social-ecological systems framework was applied to the bee-human system of commercial beekeeping to characterise beekeeping as an SES (Objective 2) by identifying the social and ecological components of a beekeeping system and how they interact to form a system. This understanding enabled the identification of important pressures and their effects on interconnected SES components. Using a case study of the migratory beekeeping in Western Australia (WA), the first conceptualization of the beekeeping SES using Ostrom's SESF was presented in Chapter 4, in which 168 variables and three priority pressures for the WA beekeeping SES were identified.

Research presented in Chapter 4 contributes to applied social-ecological theory by establishing an approach for developing a sector-specific SESF; the need for sector-specific SESFs for capturing lower tier variables unique to a particular system (e.g., sea-bed tracts in benthic small-scale fisheries; Basurto et al. (2013)) as identified in (Partelow, 2018)). Similar to the role of a medical practitioner, a sector specific SESF provides a tool for diagnosing the impact of environmental pressures on an SES (e.g., beekeeping), allowing for improved environmental management (McGinnis & Ostrom, 2014; Ostrom & Cox, 2010). The identification of key social and ecological elements and an understanding of the structural interconnectivities within the beekeeping SES have revealed the manifestation of pressures which threaten the sustainability of the industry. Furthermore, the strong dependence on stakeholder knowledge for the construction of a beekeeping sector specific SESF has emphasised the key role of local stakeholder knowledge in SES management; as highlighted by Biggs et al. (2021); Colding and Barthel (2019) and Galbraith et al. (2017). The systemic understanding of beekeeping has enabled a strong foundation for modelling complex SES interactions and associated patterns to assess the impacts of sustainability pressures on the beekeeping system.

7.3.2 Modelling SES interconnectivity

The framework presented in Chapter 4 identified beehive migration as a relatively understudied but critical SES interaction involving the intrinsic interconnectivity between the state of forage and beekeeper migration decision-making. Integrated modelling (IM) enables a systematic investigation of complex SES interconnections and feedback through a coupling of socioeconomic and environmental models (Hamilton et al., 2015). While advances in integrated SES modelling continues to provide novel solutions for understanding complex systems, operationalising a conceptual framework using scenario modelling tools that address sustainability issues, remains an active area of research (Elsawah et al., 2020; Gain et al., 2020).

This thesis provides a significant original contribution to this area of research through the development of an integrated modelling approach. *B-Agent* represents key SES interconnectivities (i.e., forage-landscape and beehive migration decision-making) within the migratory beekeeping SES, providing a tool to assess the impacts of a range of pressures on the beekeeping system. There have been other modelling approaches examining migratory beekeeping behaviours and the impacts of environmental pressures (Albayrak et al., 2021; Becher et al., 2014; Champetier et al., 2014; Pilati & Fontana, 2018), but this is the first time that an integrated model representing key SES interconnectivities between a forage-landscape and beehive migration decision-making has been developed.

The primary objective for the development of *B-Agent* was to provide a novel application of integrated modelling techniques that can improve our understanding of how the impacts of SES pressures on one component of a system propagates to interconnected counterparts. Through the development of a systemic understanding of the beekeeping SES, three priority pressures impacting beekeeping were identified, namely i) availability, access and utilization of forage sites; ii) burning of forage resources, and iii) climate change. Each of these pressures was found to be affecting forage resources and consequently, various interconnected system components. The critical interconnections between forage resource environments and beekeeper's apiary site selection have been increasingly recognised (Galbraith et al., 2017; Pantoja et al., 2017; Zoccali et al., 2017). To represent these interconnections, *B-Agent* integrates species distribution modelling (SDM) and an agent-based model (ABM) to simulate the beehive migration processes. Again, stakeholder knowledge played a key role in the *B-Agent* architecture. Specifically, stakeholders' knowledge was extracted through interviews and participatory mapping to identify target bee forage species, their geography, and important decision-making processes used in selecting suitable locations for beehive migration. This information provided the foundation for *B-Agent,* where thirty key bee forage species were identified and the geographic distribution of each was predicted under current and future climate scenarios using a machine-learning SDM algorithm (Chapter 5). Outputs from the SDM were then combined to develop a geographic representation of forage-availability as an input to an ABM representing beehive migration (Chapter 6).

The diversity of forage required to maintain a healthy and productive bee colony (Goulson et al., 2015; vanEngelsdorp & Meixner, 2010) illustrates the importance of access to multi-species forage landscapes. However, modelling these diverse landscapes to examine natural and anthropogenic pressures on bee forage is difficult as species respond differently to local environmental conditions. SDMs allows for modelling the distribution of individual species, latter combined to model distributions of multiple species to represent a species assemblage (Elith & Leathwick, 2009; Guisan & Rahbek, 2011). Here, an SDM was used to identify the change in current geographic distributions of key bee forage species in WA relative to future climate (Objective 3). Then, the SDMs for 30 individual species were collated to help describe the availability of bee forage now and under a future climate scenario. There have been SDM studies predicting change in distributions of some of the species used in this research (Gonzalez-Orozco et al., 2016; Hamer et al., 2015; Parker et al., 2003; Yates et al., 2010) however, this thesis is the first to present the application of a multi-species SDM for predicting the change in distribution of bee forage assemblages.

Integrating SDMs in social-ecological simulation models provides estimates of future resource distributions, which can help in the understanding of expected social-ecological responses to climate change (Miller & Morisette, 2014). The dynamic relationships describing how species interact with forage resources has been studied using an integrated SDM – ABM framework. For example, in a study of oilbirds (*Steatornis caripensis*, known locally as *guácharo* in its native habitat in northwest South America), the dynamic relationship between the spatial configuration of biotic resources and oilbird movement was simulated in order to replicate how an individual bird consumes resources and expends energy (Holloway, 2018). The research presented here provides a similar approach, using SDM-ABM integration for examining the dynamics of beehive migration within the context of bee forage availability. However, unlike oilbird migration, beehive migration is driven by a beekeepers' decision-making process to select the optimum sequence of forage sites (Pilati & Fontana, 2018). As such, simulating human-decision making adds another layer of complexity to the model, making the process even more challenging (Elsawah et al., 2020). *B-Agent* however, addresses this challenge by incorporating heuristic decision rules for beekeepers within the modelling process.

The relationship between migratory beekeeper behaviours and the forage environment has been examined more recently (Albayrak et al., 2021), where an ensemble learning approach (using Random Forest and Decision Tree algorithms) was used to classify landscape suitability for beekeeping (i.e., 1 = 'very bad' to 5 = 'very good') based on decadal meteorological and honey production data. The model incorporates beekeeper behaviour (i.e., pollen collecting for colony building and nectar collecting for honey production) to identify regions with 'high' and 'very high' suitability. While such approaches highlight the importance of good quality forage regions (by constraining beekeeping to regions with 'good' and 'very good' forage), it does not include adaptive decision-making by beekeepers that can explain how the migratory behaviour of beekeepers changes when external pressures impact forage availability and requires alterations to the decision-making process. By using both an ABM and SDM within the *B-Agent* architecture, I was able to explicitly represent beekeeper decision-making that adapts to the availability of forage (Objective 4). Furthermore, while Albayrak et al. (2021) had the advantage of spatial-temporal honey production data to train their machine learning model, the approach presented in Chapter 6 is particularly useful for data poor beekeeping systems.

Long distance travel for the management of migratory beehives is integral to the migratory beekeeping SES. However, travel over long distance not only results in increased costs to honey production (Pignagnoli et al., 2021), but can also result in the loss of bee populations (Melicher et al., 2019). For the WA beekeeping SES, fuel cost was identified as one of the major expenses involved in beekeeping, which can affect the decisions making of commercial and semi-commercial beekeepers differently (i.e., semi-commercial beekeepers generally restrict movement within 300km from the home). A systemic understanding of the WA beekeeping SES (Chapter 4) has highlighted that increased length and frequency of travel due to changing spatial-temporal availability of forage resources is a possibility. The SDM results of thirty key forage species revealed significant variability in the distribution of target bee forage species, with the majority contracting their current distributions and shifting laterally and/or poleward. Similarly, lateral and poleward shifts were reported in previous SDM studies discussed in Chapter 5.

Finally, when the future distributions of key forage species were used as inputs to *B-Agent*, three key patterns of hive migration emerged: (i) the mean annual distance travelled for commercial beekeepers was higher than semi-commercial beekeepers, (ii) the frequency of beehive migration increased up to six times per year, and (iii) the spatial distribution of forage site harvested by beekeepers shifted inland (eastward). These patterns were known to exist within the systems based on stakeholders' information (Chapter 4). Emergent behaviour of the modelled agents resembles the key behaviours observed in the real systems (e.g., modelled agents change migration patterns when forage availability changes), the model is considered suitable for mapping the responses to environmental change (Gallagher et al., 2021). The ability of an ABM to reproduce multiple patterns observed in the real system is a novel approach used for validation of ABMs (Wang et al., 2018). Emergence of the known patterns from key behaviours of modelled agents within the beekeeping system provided structural validation for *B-Agent*.

7.4 Considerations and recommendations for future research

The research presented here provides results for the first attempt at modelling structural interconnectivities within the commercial beekeeping social-ecological system. Being a novel application, there are several recommendations which should be considered for future research.

This thesis is founded on a holistic view of the bee-human system. First, Chapter 3 of the thesis begins by identifying the important thematic areas that this research addresses, with the remainder of the thesis focuses on defining commercial migratory beekeeping as an SES to model decision making processes. This opens the door for future research into questions identified in Chapter 3 including, (i) are there critical thresholds of bee species diversity and/or bee population abundance beyond which there are significant impacts to meeting SDG targets, and do these thresholds vary across space and time; and (ii) what ecosystem services can be optimized with existing bee diversity within a region, to what extent can they contribute to achieving SDG targets, and does the introduction of managed species enhance or suppress existing ecosystem services in order to ensure the sustainability of bee systems.

This thesis presents the first sector-specific SESF for beekeeping (Chapter 4) which can now be applied to investigate a range of sustainable development scenarios within both stationary and migratory beekeeping in different geographic settings. For example, understanding structural interconnectivities and stakeholder knowledge, could inform land restoration approaches aimed at stationary beekeeping (e.g., Picknoll et al. (2021)) through a better understanding of system pressures. For example, understanding of changing environmental suitability of bee forage species can inform land restoration and plantation approaches to support beekeeping. In addition, extending the beekeeping-SESF to stationary beekeeping or beekeeping using species other than *Apis mellifera* (e.g., stingless beekeeping in Meliponiculture) could identify additional lower tier variables and improve transferability of the beekeeping-SESF developed here to other regions. If such an approach was used, the decision-making rules found within *B-Agent* could be adapted to account for the new social-ecological setting. Moreover, the cross-scale nature of an SES extends the effects of SES interactions beyond local (Biggs et al., 2021). How the dynamics of beekeeping interactions affect other interconnected systems can be looked into for future research.

The novel modelling application presented in this thesis is the first of its kind, with great potential for further development and improvement. For example, future research could refine the flowering phenology assumptions used in the model to incorporate satellite derived near real-time flowering predictions (e.g., Dan J. Dixon et al. (2021)). Furthermore, the use of loose coupling integration in *B-Agent*, where the forage environment is created based on input layers, opens the possibility for integrating other modelling outputs to further refine forage availability environments or test an alternative scenario. For example, an additional scenario of burning forage resources can be tested by importing spatial data and updating relevant variables (e.g., re-usability of forage site after last burn) for individual forage sites. Although critical and important to acknowledge, the effects of climate change on bee species and the growth and phenology of melliferous flora was beyond the scope of this research. However, including these aspects in future work could greatly enhance the current capabilities of *B-Agent.*

An intriguing aspect to investigate in future work is the introduction of various land management regimes and associated hive migration dynamics. For example, extending *B-Agent* by assigning landownership and/or land tenure to each forage site and updating migration decisions with the preference for particular land ownership/tenure could be extremely useful in addressing other pressures impacting the beekeeping systems including two priority pressures (i) availability, access and utilization of forage sites, and (ii) burning of forage resources as identified in Chapter 4. Such an extension could introduce the role of land managers as additional agents within *B-Agent*, which could further identify new system patterns that might be useful for informing resource management approaches.

7.6 Summary and Conclusions

This thesis presents a novel body of research advancing the existing knowledge of bee-human systems specifically, examining the importance of understanding social-ecological interconnectivities of beekeeping to address the impacts of industry pressures through a case study of the impacts of climate change on commercial beekeeping in Western Australia. In a broader sense, this research has defined the social-ecological aspects of bee-human systems in order to address sustainability challenges.

This research has provided tangible answers to the question of how SES understanding of beekeeping systems can inform spatial planning and management of natural resources. The conceptual understating of bee-human systems has been developed with an application of Ostrom's SESF to characterize the beekeeping SES. Stakeholder knowledge and decision-making have a crucial role in addressing sustainability pressures affecting SESs. Understanding structurally interconnected SES components can provide important insights into how various pressures manifest within the system. Addressing SES sustainability challenges requires the integration of local knowledge of stakeholders, spatial landscapes, and individual decision-making to design informed, spatially targeted environmental management approaches. This research presents an example of such an approach by presenting an evidence base to demonstrate structural interconnectivities, while highlighting the importance of tools and approaches for informing management decisions that ensure the sustainability of an SES.

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APPENDIX 1 - PUBLICATION IN AMBIO

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PERSPECTIVE

Why bees are critical for achieving sustainable development

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Abstract Reductions in global bee populations are threatening the pollination benefits to both the planet and people. Whilst the contribution of bee pollination in promoting sustainable development goals through food security and biodiversity is widely acknowledged, a range of other benefits provided by bees has yet to be fully recognised. We explore the contributions of bees towards achieving the United Nation's Sustainable Development Goals (SDGs). Our insights suggest that bees potentially contribute towards 15 of the 17 SDGs and a minimum of 30 SDG targets. We identify common themes in which bees play an essential role, and suggest that improved understanding of bee contributions to sustainable development is crucial for ensuring viable bee systems.

Keywords Bees · Biodiversity · Complex systems · Human environment interactions · Pollination · Sustainable Development Goals

INTRODUCTION

The United Nations' 17 Sustainable Development Goals (SDGs) are designed to achieve synergy between human well-being and the maintenance of environmental resources by 2030, through the pursuit of 169 targets and more than 200 indicators (UN 2015). The biosphere is the foundation for all SDGs (Folke et al. 2016; Rockström and Sukhdev 2016; Leal Filho et al. 2018), and yet biodiversity conservation remains a persistent global challenge (Tittensor et al. 2014). An examination of how a particular suite of organisms within the global wealth of biodiversity can contribute to the attainment of the SDGs holds the potential to link sustainable development policy with conservation through the design of integrated solutions. We explore the interconnections between bees a critical group of insects with diverse economic, social, cultural and ecological values and people, in the context of the SDGs.

BEES, PEOPLE AND THE PLANET

Bees comprise ~ 20 000 described species across seven recognised families (Ascher and Pickering 2014), with many more species yet to be described (Fig. 1). The evolutionary radiation of bees coincided with the evolutionary radiation of flowering plants (Cappellari et al. 2013), and bees occupy an important ecological role as pollinators of a range of flowering plant species. Although bees are not the most diverse group of pollinators (butterflies and moths comprise over 140 000 species), they are the most dominant taxonomic group amongst pollinators; only in the Arctic regions, is another group (flies) more dominant (Ollerton et al. 2017). The ability of bees to transport large numbers of pollen grains on their hairy bodies, reliance on floral resources, and the semi-social or eu-social nature of some species are amongst the characteristics that make bees important and effective pollinators (Ollerton et al. 2017; Klein et al. 2018). Fifty bee species are managed by people, of which around 12 are managed for crop pollination (Potts et al. 2016a).

The potential importance of bees for crop pollination has been highlighted as a particular reason to conserve wild bees and their habitat (Klein et al. 2007; Gill et al. 2016; Potts et al. 2016a; Klein et al. 2018). More than 90% of the world's top 107 crops are visited by bees; however, wind- and self-pollinated grasses account for around 60% of global food production and do not require animal pollination (Klein et al. 2007). Wild bees contribute an average of USD\$3 251 ha^{-1} to the production of insect-pollinated

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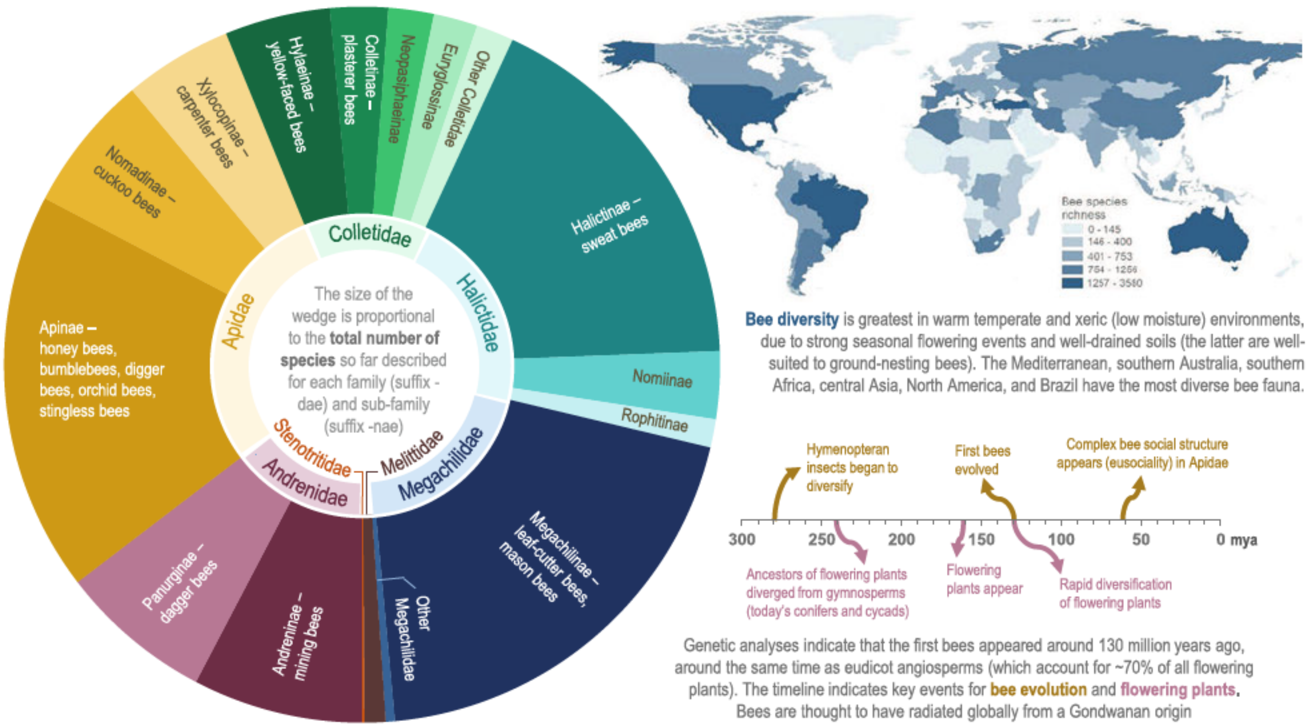

Fig. 1 A snapshot of the diversity of bees. Bees are taxonomically classified under the insect Order Hymenoptera, along with ants, wasps and sawflies, and are part of the superfamily Apoidea, and clade Anthophila, with seven recognised families. Although only 50 of the ~ 20 000 described bee species are actively managed by people, the entire clade is important for ecosystem functioning and human well being. Bees and flowering plants have co evolved, making bees effective pollinators of a large proportion of flowering plant species. There are perhaps a further ~ 5 000 bee species that are yet to be described. Data source: Ascher and Pickering (2014). Information for this figure was sourced from Michener 1979; Michener 2000; Michez and Patiny 2007; Litman et al. 2011; Cappellari et al. 2013; Peters et al. 2017; Meiners et al. 2019

crops, similar to that provided by managed honey bees (Kleijn et al. 2015). A very small number of mostly common wild bee species provide the majority of bee-related crop pollination services (Kleijn et al. 2015), and other insects such as flies, wasps, beetles, and butterflies have an important, underemphasised role in crop pollination (Rader et al. 2016). Such research has highlighted the danger of exclusively highlighting the importance of bees for crop pollination, to the potential detriment of conserving diversity across the landscape (Kleijn et al. 2015; Senapathi et al. 2015). In our assessment of bees and the SDGs, we highlight that the diversity of wild and managed bees has crucial ecological, economic and social importance including and beyond crop pollination.

Long-standing associations exist across multiple bee species and human societies. Documented ancient bee people interactions include honey hunting dating back to the Stone Age for the honey bee *Apis mellifera* in Europe (Roffet-Salque et al. 2015), more than 2 000 years of keeping the honey bee *Apis cerana* in Asia (Crane 1995), and beekeeping reaching back to at least pre-Columbian times for stingless bees (*Melipona beechii*) in Mayan Mexico (Quezada-Euán 2018). Bees also appear in many religious scriptures and are found within mythology, cosmology and iconography (Fijn 2014; Roffet-Salque et al. 2015; Potts et al. 2016a; Quezada-Euán 2018). Beeswax from culturally significant sugarbag bees (*Tetragonula* spp.) has been used in the production of rock art by Aboriginal peoples in northern Australia for at least 4 000 years (Watchman and Jones 2002). In Greek society, bees are closely linked with the cycle of birth and death, and considered an emblem of immortality (Cook 2013). "Telling the bees" was a popular tradition in 19th Century New England; it was customary for keepers to inform their bees of any major event such as a birth, death, marriage or long journey (Hagge 1957). These reciprocal bee human relationships have historic legacy and are highly important for informing current practices around bee management.

Today, the long-standing mutualistic relationship between bees and people is jeopardised by recent reported declines in bee populations (Potts et al. 2016b). The loss of managed honey bee colonies (e.g. Potts et al. 2010) and declines in wild bee pollinators (e.g. Biesmeijer et al. 2006; Koh et al. 2016) have been observed, particularly in Europe and North America. However, much remains undocumented about the conservation status of most bee species

(Goulson et al. 2015; Jamieson et al. 2019). The global conservation status of just 483 bee species has been assessed by the IUCN, most of which were ‘data deficient’ (IUCN 2019). The European Red List assessment of 1 965 species of European bees found that 9.2% were threatened, whilst insufficient data were available to assess the conservation status of nearly 57% of European species; many of these may also be threatened (Nieto et al. 2014). Goulson et al. (2015) reason that declines in wild bees definitively noted for Europe and North America are likely to have occurred elsewhere.

With a decline in bee populations, there has been a surge of research focusing on the drivers of bee decline and the impacts on provisioning ecosystem services (Goulson et al. 2015; Decourtye et al. 2019). Drivers such as habitat loss, pesticide use, the proliferation of parasites, availability and diversity of forage, change in land use and climate, and species competition have all contributed to the reduction in bee populations (Goulson et al. 2015; Sánchez-Bayo and Wyckhuys 2019; Wagner 2020). These drivers interact in complex ways; for example, market-driven agricultural intensification has limited bees’ access to forage resources and at the same time potentially increasing bees’ exposure to harmful agrichemicals (Durant 2019; Sánchez-Bayo and Goka 2014). People can act as a positive influence for ecosystem function through designing bee-friendly policies and contributing to bee conservation approaches (Potts et al. 2016a; Matias et al. 2017; Hill et al. 2019). Acknowledging the plethora of literature addressing the decline in bee populations and the consequences for agriculture, we contend that the ubiquitous importance of bees in connecting the planet and people remains relatively less explored, particularly with regard to broader goals in sustainable development.

FRAMING THE BROADER IMPORTANCE OF BEES TO SUSTAINABLE DEVELOPMENT

Bees provide a range of ecosystem services that contribute to the wellbeing of people whilst maintaining the planet’s life support systems (Gill et al. 2016; Matias et al. 2017). Ecosystem services inherently contribute to achieving global sustainable development (Wood et al. 2018). Yet the extent to which bees contribute towards the achievement of the full suite of the SDGs has not been explored in detail. Existing research has highlighted the importance of insects in achieving multiple SDGs through the regulation of natural cycles, biological pest control, pollination, seed dispersal, and even as bio-inspiration (Gill et al. 2016; Sánchez-Bayo and Wyckhuys 2019; Dangles and Casas 2019). Bee pollination has been identified as directly contributing to food security (SDG2) and biodiversity (SDG15) (Dangles and Casas 2019). However, bees could also contribute to a broader range of SDGs.

We explicitly identify the realised and potential contributions of bees towards achieving the SDGs, presenting evidence to highlight the interconnectedness between bees, people and the planet from an integrated system perspective (Stafford-Smith et al. 2017). We review the SDGs alongside the potential contributions of bees in achieving individual SDG targets. As the SDGs explicitly build on the foundation of the biosphere (Folke et al. 2016; Leal Filho et al. 2018), the perspective presented here may help in designing implementation pathways to achieve SDG targets. We identify 30 targets to which bees may contribute (Table 1) through a range of direct and indirect connections between bees, people and the planet.

We incorporate contributions from all bee species, including wild and managed populations. The European honey bee (*A. mellifera*) and buff-tailed bumblebee (*Bombus terrestris*) could be considered as ‘massively introduced species’ having greatly expanded their geographic range through human management and escape (Geslin et al. 2017). We note the extensive and evolving literature on the interactions between native wild bees, introduced domesticated bees, and feral bees, noting evidence of competition for forage and nesting resources, disruption of native plant pollinator networks, and potential for viral disease transmission between species (e.g. Geslin et al. 2017; Mallinger et al. 2017; Wojcik et al. 2018; Alger et al. 2019; Murray et al. 2019; Valido et al. 2019). We pursue a holistic perspective that encompasses native wild and managed introduced bees, following Kleijn et al.’s (2015, 2018) calls for an inclusive approach that safeguards all pollinators.

THE IDENTIFIED CRITICAL ROLE OF BEES IN SUSTAINABLE DEVELOPMENT

The importance of bee pollination for food crops has been widely acknowledged, with growing concern of a global crisis as demand for pollination services continues to outstrip supply, with an associated increase in less diverse, pollinator-dependant agriculture systems (Aizen and Harder 2009; Aizen et al. 2019). In addition to improving the yield of some crops (target 2.3) (Klein et al. 2007, 2018; Stein et al. 2017), bee pollination contributes to enhanced nutritional value (target 2.2) and improved quality and longer shelf life of many fruits and vegetables (Klatt et al. 2014), which could potentially help in reducing food waste (target 12.3) resulting from aesthetic imperfections (Gunders and Bloom 2017).

Less-explored aspects of bee pollination include the contribution to biofuels (SDG7). Despite being self-

Table 1 The contributions of bees towards relevant SDG targets

Sustainable development goal (SDG)[a]	Contributions from bees to SDG targets	Examples of supporting literature[b]	Details on the contributions that bees may provide towards achieving the SDG targets
1. No Poverty	1.1 1.4 1.5	Bradbear, 2009; Amulen et al. 2019; Pocol and McDonough 2015	Keeping bees offers economic diversity as an income source (1.1) helping build resilient livelihoods for poor and vulnerable peoples (1.5), whilst potentially providing equal access to economic and natural resources for both men and women (1.4)
2. Zero hunger	2.2 2.3	Klein et al. 2007; Kleijn et al. 2015; Potts et al. 2016a; Stein et al. 2017; Klein et al. 2018	Bee pollination increases crop yield (2.3) and enhances the nutritional value of fruits, vegetables, and seeds (2.2)
3. Good health and well being	3.4 3.8 3.9	Bradbear, 2009; Brockerhoff et al. 2017; Pasupuleti et al. 2017; Sforcin et al.2017; Kocot et al. 2018; Easton Calabria et al. 2019;	Bee products provide safe and affordable medicinal sources (3.8) used in traditional and modern medicine to treat non communicable diseases such as cancer through strong bioactive compounds (3.4). Bee pollination potentially contributes to the growth and diversity of plants that are important for improved air quality (3.9)
4. Quality education	4.3 4.4 4.5	Pocol and McDonough 2015; Mburu et al. 2017; Ekele et al. 2019	Vocational training for keeping bees can enhance equal opportunities for employment, training and entrepreneurship amongst men, women and indigenous people (with traditional knowledge) (4.3, 4.4 and 4.5).
5. Gender equality	5.5 5.a	Pocol and McDonough 2015; Mburu et al. 2017	Keeping bees as a hobby or being involved in beekeeping can enhance opportunities for women's involvement in economic, social and political decision making processes even in communities that deprive women of property rights (5.5, 5.a)
6. Clean water and sanitation	6.6	Brockerhoff et al. 2017; Creed and van Noorwijk 2018	Bee pollination may contribute to growth and diversity in water related ecosystems, such as mountains and forest. Appropriate afforestation efforts may provide new resources for commercial bee operations whilst potentially contributing to regional water supply (6.6)
7. Affordable and clean energy	7.2	Romero and Quezada Euán 2013; Halinski et al. 2018; Perrot et al. 2018	Bee pollination improves production for oilseed crops used as biofuel such as sunflower, canola and rapeseed (7.2)
8. Decent work and economic growth	8.1 8.6 8.9	Arih and Korošec 2015; Mazorodze 2015; Pocol and McDonough 2015; Stein et al. 2017; Quezada Euán 2018; Vinci et al. 2018	Improved agricultural production from bee pollination may contribute to the gross domestic product (GDP) of nations (8.1). Beekeeping can diversify livelihood opportunities for men and women in rural areas (8.6) and support nature based tourism initiatives (8.9).
9. Industry innovation and infrastructure	9.b	Xing and Gao 2014; Zhang et al. 2015; Sahlabadi and Hutapea 2018	Bees are an element of nature that inspires human innovations (e.g., airplane design and computer algorithm development) and new honey related products (9.b)
10. Reduced inequality	10.1 10.2	Carroll and Kinsella 2013; Tomaselli et al. 2014; Mburu et al. 2017	Improved livelihoods from beekeeping and the contribution of bee pollination towards GDP can support sustainable income growth for lower income groups (10.1) which can potentially contribute to promoting inclusive social, economic and institutional development (10.2)
11. Sustainable cities and communities	11.6 11.7	Lowenstein et al. 2015; Van der Steen et al. 2015; Hausmann et al. 2016; Stange et al. 2018; Zhou et al. 2018	Bees can be useful in monitoring air quality in urban areas, as pollination of urban flora can support improved local air quality (11.6). Bees can enhance pollination and self sustainability of urban gardens and public open spaces (11.7)

Table 1 continued

Sustainable development goal (SDG)[a]	Contributions from bees to SDG targets	Examples of supporting literature[b]	Details on the contributions that bees may provide towards achieving the SDG targets
12. Responsible consumption and production	12.3 12.b	Klatt et al. 2014; Lemelin 2019	Bee pollination can contribute to reducing food waste by improving visual aesthetics of food (shape, size and colour) and increase shelf life (12.3). Beekeeping can be marketed as sustainable tourism for regional development (12.b)
13. Climate actions	13.3	Van der Steen et al. 2015; Smith et al. 2019	Use of bees and bee products for environmental monitoring can improve understanding of climate impacts on the environment (13.3)
14. Life below water	14.4	Amjad Khan et al. 2017	Bees can potentially contribute to improved production of plant based sources of compounds commonly found in fish. Overharvesting of fish can be managed by promoting production and consumption of alternative plant based nutrient sources (14.4)
15. Life on land	15.1 15.5 15.9	Senapathi et al. 2015; Minja and Nkumilwa 2016; Chanthayod et al. 2017; Klein et al. 2018; Mudzengi et al. 2019	Bees contribute to biodiversity by pollinating flowering trees and plants (15.5) and beekeeping can contribute to forest conservation (15.1). Incorporating beekeeping in local planning processes may support reforestation activities which can result in poverty reduction and sustainable regional development (15.9).

[a]SDG16 (peace, justice and strong institutions) and SDG17 (partnership for the goals) were excluded from this analysis given their focus on governance and policy

[b]Supporting literature includes a mix of direct and indirect evidence. The details on bees' potential contribution to SDGs have been provided using the language used in SDG targets, which may differ from the language used in the supporting literature

pollinated, oil seed crops show increased yield when pollinated by bees (target 7.2) (Halinski et al. 2018; Perrot et al. 2018). Research in Mexico on the performance of bees on *Jatropha curcas* found significant improvement in the seed set when the self-pollinated varieties were supported with bee pollination (Romero and Quezada-Euán 2013). Canola, another self-pollinating oilseed crop, also shows a positive association between higher yields and bee diversity (Halinski et al. 2018).

Beyond agricultural landscapes, research in urban bee ecology aids understanding of bee dynamics in our cities and informs urban bee conservation initiatives (Hernandez et al. 2009; Stange et al. 2017). Urban beekeeping strengthens residents' connection to nature (Stange et al. 2018). Planting aesthetically pleasing, bee-attractive flowering species in landscape planning can provide forage for bees, and close proximity to such plantings may result in pollination rewards for trees and other species in public green spaces (target 11.7) (Lowenstein et al. 2015; Hausmann et al. 2016). European honey bees can be used as an indicator species for tracking contaminants and monitoring environmental health (target 13.3) in urban areas (Zhou et al. 2018). In addition, understanding bee forage preference, suitability of habitat and mobility between different habitat types is critical for designing sustainable urban (target 11.7) and rural landscapes (target 15.9) to optimize pollination benefits as well as support bee health (Stange et al. 2017; Langellotto et al. 2018). For example, the United Kingdom's Protection of Pollinators Bill was proposed to develop a national network of wildflower corridors called B-lines to support bee populations and other pollinators (UK Parliament, House of Commons, 2017).

The contribution of wild and managed bees in pollinating wild plants in natural ecosystems and managed forests (target 15.1) is well-acknowledged (Senapathi et al. 2015; Klein et al. 2018). The biodiversity found within forests provides a critical range of ecosystem services including water cycle regulation (target 6.6) and carbon sequestration (Brockerhoff et al. 2017; Creed and van Noordwijk 2018). Bee-pollinated plants provide a source of food for wildlife and non-timber forest products for people (Bradbear, 2009; Senapathi et al. 2015). For example, Brazil nut trees (*Bertholletia excelsa*) require bee pollination to set their high-value fruit, with much greater productivity in the wild, likely due to low numbers of native bees in plantations (Cavalcante et al. 2012). Beekeeping within forest boundaries can support forest conservation (target 15.1) alongside rural livelihoods (Sande et al. 2009; Chanthayod et al. 2017; Mudzengi et al. 2019).

Keeping bees provides opportunities for income diversity (target 1.1) with low start-up costs, through diverse products and services including honey, pollen, beeswax, propolis, royal jelly, and pollination services (Bradbear 2009). Initiatives to promote beekeeping and pollination services in Kenya have resulted in livelihood improvements for smallholder farmers through increased farm productivity and an additional income stream (target 1.5) (Carroll and Kinsella 2013). However, in other regions of Africa, constraints to improve livelihoods through bee-related activities have been attributed to a lack of knowledge concerning bee husbandry processes, access to equipment, and training (Minja and Nkumilwa 2016). Vocational education in beekeeping (target 4.3) could promote economic opportunities for employment and entrepreneurial enterprise (targets 8.6 and 4.4) and diversification for Indigenous groups (targets 1.4 and 4.5), as well as help empower women (target 5.5) including those within traditionally patriarchal societies to promote gender equality (target 5.a) (Pocol and McDonough 2015; Mburu et al. 2017).

Beekeeping can be an important strategy for livelihood diversification (Bradbear 2009), which can directly contribute to an increase in per capita and household income (target 8.1) (Mazorodze 2015; Chanthayod et al. 2015) and also allow for enhanced fiscal opportunities (e.g. tourism) and sustained income growth for people in rural areas, irrespective of social and economic status (targets 10.1 and 10.2) (Pocol and McDonough 2015; Vinci et al. 2018). An initiative for sustainable tourism in Slovenia packages bee-related education and healing experiences with bee products, together with opportunities to create and purchase original crafts using bee products (Arih and Korošec 2015). In Fiji, The Earth Care Agency is working to promote organic honey production on remote islands to provide economic alternatives for indigenous Fijians (Matava Fiji Untouched 2019). These initiatives contribute to local economies and in the case of Slovenia (Arih and Korošec 2015), help in marketing the country's natural attractions whilst providing additional livelihood opportunities through increased tourism activities (target 8.9).

In relation to health, honey, bee pollen, propolis, royal jelly, beeswax and bee venom have all been used in traditional and modern medicine (target 3.8) (Kocot et al. 2018; Easton-Calabria et al. 2019). Researchers have identified bioactive properties of honey, propolis and royal jelly which suggest the presence of compounds with antimicrobial, anti-inflammatory, antioxidant, antitumor, and anticancer activities (Pasupuleti et al. 2017; Kocot et al. 2018; Easton-Calabria et al. 2019). Honey is used in wound and ulcer care, to enhance oral health, fight gastric disorders, and liver and pancreatic diseases, as well as to promote cardiovascular health (Pasupuleti et al. 2017; Easton-Calabria et al. 2019). Propolis is used in gynaecological care, oral health, dermatology care, and oncology treatments, whilst royal jelly is used in reproductive care, neurodegenerative and aging diseases, and wound healing (target 3.4) (Pasupuleti et al. 2017).

Bees have contributed to industry, innovation and infrastructure by inspiring the design and development of a range of structures, devices and algorithms that can benefit sustainable development (target 9b). The honeycomb structure of beehives is often a mainstay in structural engineering (Zhang et al. 2015). Drawing inspiration from bee anatomy, the medical industry has benefited from innovations such as surgical needles adopted from the design of bee stingers (Sahlabadi and Hutapea 2018). Bee behaviour has inspired complex computer-based search and optimisation processes informing a new wave of genetic algorithms (Xing and Gao 2014).

TOWARDS SUSTAINABLE BEE SYSTEMS

The decline in global insect populations has attracted the attention of the scientific community, general public and policymakers (Potts et al. 2016a), with heightened public awareness of the importance of bees for pollination. Our research has highlighted the contribution bees can provide towards achieving a diverse range of SDG targets in addition to their crucial role in pollination. The increasingly positive attitude of the public towards bees, and insect pollinators more broadly, provides opportunities for efforts to conserve bee habitat and support pro-pollinator initiatives in land management, agricultural diversification and urban greening (Senapathi et al. 2015; Schönfelder and Bogner 2017).

A holistic view of ecosystems including wild and managed bees and humans is necessary to address sustainability challenges (Kleijn et al. 2018; Saunders et al. 2018). By employing a system approach, we can better understand the interconnections between elements within coupled human environment systems. We strongly advocate the need for appropriate natural resource management approaches for maintaining sustainable systems as vital for allowing the continued success of bees in their natural role. We summarise our findings by suggesting eight key thematic priority areas whereby bees can play a crucial role in meeting the SDGs (Fig. 2).

These themes provide a foundation for an emerging, yet urgently needed research agenda to explore the complex relationship between bees, people and the planet. A range of important questions should guide this research agenda including: (i) What social and ecological entities contribute to a bee human system, what feedback and trade-offs exist

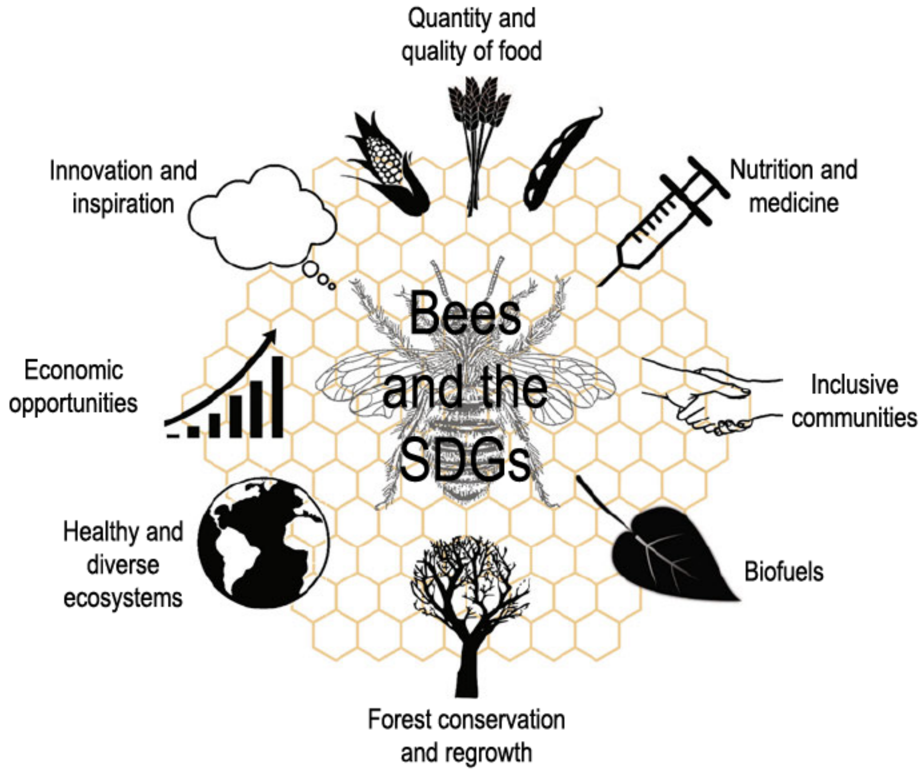

Fig. 2 Bees and the SDGs. Overarching themes whereby bees contribute to sustainable development targets

amongst these entities, and how can understanding structural interconnectivities within this bee human system contribute to sustainable decision making at various spatial scales? (ii) Are there critical thresholds of bee species diversity and/or bee population abundance beyond which there are significant impacts to meeting certain SDG targets, and do these thresholds vary by geographic regions? (iii) What ecosystem services can be optimized with existing bee diversity in a region, to what extent can they contribute to achieving SDG targets, and does the introduction of managed species enhance or suppress existing ecosystem services? In addition, the distinct roles of wild and managed bees provide a further research lens for identifying the critical role that bees can provide in achieving the SDGs. We must strive to restore balance and reverse bee decline trajectories if we are to encounter a future in which bees continue to contribute to the sustainable development of society.

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APPENDIX 2 - PUBLICATION IN ECOLOGY AND SOCIETY

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Research

Using a social-ecological system approach to enhance understanding of structural interconnectivities within the beekeeping industry for sustainable decision making

Vidushi Patel [1,2], *Eloise M. Biggs* [3], *Natasha Pauli* [1,3] and *Bryan Boruff* [1,2,3]

ABSTRACT. The social-ecological system framework (SESF) is a comprehensive, multitiered conceptual framework often used to understand human-environment interactions and outcomes. This research employs the SESF to understand key interactions within the bee-human system (beekeeping) through an applied case study of migratory beekeeping in Western Australia (WA). Apiarists in WA migrate their hives pursuing concurrent flowering events across the state. These intrastate migratory operations are governed by biophysical factors, e.g., health and diversity of forage species, as well as legislated and negotiated access to forage resource locations. Strict biosecurity regulations, natural and controlled burning events, and changes in land use planning affect natural resource-dependent livelihoods by influencing flowering patterns and access to valuable resources. Through the lens of Ostrom's SESF, we (i) identify the social and ecological components of the WA beekeeping industry; (ii) establish how these components interact to form a system; and (iii) determine the pressures affecting this bee-human system. We combine a review of scholarly and grey literature with information from key industry stakeholders collected through participant observation, individual semistructured interviews, and group dialog to determine and verify first-, second-, and third-tier variables as SESF components. Finally, we validate the identified variables through expert appraisal with key beekeepers in the industry. Our results identify the governance system, actors, resource system, and resource units comprising the beekeeping industry in WA. Using this approach, we identify three principal system pressures including access to apiary sites, burning of forage, and climate change impacts on the system, which influence the SES and its sustainability. Our approach provides for an improved understanding of SES complexities and outputs that should be used to support improved sustainable management of common pooled resources to ensure effective pollination and sustained apiary production.

Key Words: *local ecological knowledge; migratory beekeeping; social-ecological system; sustainability*

INTRODUCTION

Bees and beekeeping have recently received significant attention for their contributions to sustainable development (Carroll and Kinsella 2013, Yap et al. 2015, Minja and Nkumilwa 2016, Klein et al. 2018, Vinci et al. 2018, Dangles and Casas 2019, Patel et al. 2020) and human well-being (Gill et al. 2016, IPBES 2016, Sánchez-Bayo and Wyckhuys 2019). Beekeeping involves the production of honey and other bee products as well as crucial pollination services (Pilati and Prestamburgo 2016). For more than 15,000 years, the reciprocal relationship between *Apis mellifera* (the European honeybee[1]) and *Homo sapiens* has resulted in mutually beneficial outcomes (Lehébel-Péron et al. 2016), yet the interconnectedness between these two species has only been partially explored. Initial exploration of this relationship has used a social-ecological system (SES) approach to address resource management and sustainability of wild bee-human systems (Matias et al. 2017). Yet, to our knowledge, an SES approach has not been applied to managed bee-human systems, i.e., the beekeeping industry. The honeybee-human system is unique, and like those ecosystems supporting wild bee populations, it is equally vulnerable to adverse resource management decision making (Aizen and Harder 2009, Potts et al. 2010, vanEngelsdorp and Meixner 2010).

The sustainability of a beekeeping system depends on continuous access to quality forage resources for bees to maintain healthy and productive colonies (Pilati and Fontana 2018). To access forage resources, many beekeepers, such as those in Europe and the United States of America, migrate their hives following honey flows across public and private lands (Pilati and Prestamburgo 2016, Durant 2019). Access to forage sites are often dependent on permission from authorities or through negotiation with private land owners (Hill et al. 2019). Ad hoc changes in management approaches on both private and public lands can limit access to important natural resources and impact beekeepers' livelihoods. Furthermore, because bee foraging is a landscape-scale process (Sponsler and Johnson 2015), the impact of change in landscape composition is axiomatic in the case of migratory beekeeping (Malkamäki et al. 2016, Smart et al. 2016, Galbraith et al. 2017, Evans et al. 2018).

Complex natural and anthropogenic drivers are contributing to global bee decline (Goulson et al. 2015, Wagner 2020) and are impacting on bee system contributions that support sustainable development (Patel et al. 2020). Evidence also suggests that negative interactions can occur between wild and managed bees, including resource competition, disease transmission, and plant-pollinator network disruption (Geslin et al. 2017, Mallinger et al. 2017, Valido et al. 2019). As global agricultural landscapes have become less diverse and increasingly reliant on pollinators (Aizen et al. 2019), a rise in the number of managed bee colonies has occurred to cope with the pollinator deficit (as highlighted in Aizen and Harder 2009). As a result, an increase in interactions between domestic and with wild bee populations may occur.

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However, safeguarding both wild and managed bees is critical for food production and to address wider sustainability challenges, targeted approaches that adopt a bee-human system perspective (Kleijn et al. 2018, Saunders et al. 2018, Patel et al. 2020) are required. Bee-human system sustainability implies maintaining broader bee biodiversity to ensure a sustainable supply of bee-mediated services (Patel et al. 2020).

A social-ecological systems approach provides a lens through which the bee-human relationship can be examined. To date, research has primarily focused on the benefits humans receive from bees (Bradbear 2009, Carroll and Kinsella 2013, Klein et al. 2018) rather than the reciprocal relationship between the two species. Using an SES framework, both human and natural systems can be examined in equal depth (Binder et al. 2013), providing a mechanism for understanding the complex interdependencies between the various components of both systems. Importantly, the complex feedbacks between social and ecological components contribute to the management of ecosystem service (ES) flows (Rova and Pranovi 2017). Applying an SES approach to the bee-human system allows for the identification and management of system drivers, activities, and processes that contribute to the sustainable development of the system (Matias et al. 2017) through improved environmental management and governance (Rodela et al. 2019). As such, our research aim is to characterize the beekeeping industry as an SES through identification of human and biophysical components, associated interactions, and key beekeeping processes. Acquired novel understanding of the complex interconnectivities associated with the beekeeping SES will enable facilitated management of system pressures, i.e., the availability, access, and utilization of apiary sites, and help inform integrated policy design to achieve sustainable development that is inclusive of biodiversity conservation.

Social-ecological system framework (SESF)

In this research, we focus on conceptualizing beekeeping as a social-ecological system through the lens of Elinor Ostrom's SES framework (SESF; McGinnis and Ostrom 2014), using the beekeeping industry of Western Australia (WA) as an applied case study. Ostrom's SESF was primarily designed for application to management situations in common pool resources where humans are accountable for sustainable extraction and maintenance of resources (McGinnis and Ostrom 2014, Rodela et al. 2019). The framework represents a hierarchy of multitiered interacting components under six core concepts representing the first tier; resource systems (RS), resource units (RU), governance systems (GS), actors (A), interactions (I), and outcomes (O). The core concepts are nested within the broader social, ecological, and political setting (S) accounting for feedback from, to, and between other ecosystems (Ostrom 2009, Ostrom and Cox 2010, McGinnis and Ostrom 2014). Each core concept is decomposable into a number of lower tiers, which can dictate local data collection (Ostrom 2009, Hinkel et al. 2015, Partelow 2016) for monitoring and guiding management of the system.

Ostrom's SESF has been applied to resource sectors such as forestry, irrigation, agriculture, fisheries, and watershed management (Partelow 2018). Although the framework represents bidirectional links between social and ecological systems, variable development in SESF applications has disproportionately focused on social system variables (Partelow 2018), with fewer applications adding ecological system variables (Vogt et al. 2015). Additionally, limited research has identified variables for local-level analysis (Delgado et al. 2012), those that have targeted variables to match with common terminology of the application being studied, such as socio-technical systems (Acosta et al. 2018). The uniqueness of some lower tier variables to specific sectors requires sector-specific SESFs (Basurto et al. 2013, Partelow 2018), either developed vertically by adding lower tiers under existing concepts, e.g., sea-bed tracts as a lower tier within benthic small-scale fisheries (Basurto et al. 2013), or horizontally by adding sector-specific first tier concepts, e.g., addition of transformation systems and products specific to food systems (Marshall 2015). In either approach, defining each variable relevant to the sector can improve transferability of the SESF.

Following conceptual guidance provided by Hinkel et al. (2015) and ontological logic suggested by Frey and Cox (2015), we focus on applying Ostrom's SESF for the beekeeping sector using migratory beekeeping in WA as an applied example. We advocate that our approach can be used to improve environmental management through identification of key processes involving human and biophysical components, to help ensure the long-term sustainability of the bee-human system. Our research identifies the key interactions important for understanding how various pressures can manifest across the bee-human system. To address the research aim, we explore the following questions: (i) what are the social and ecological components of the beekeeping industry; (ii) how do these components interact to form a system; and (iii) what pressures are affecting the bee-human system? We achieve this through application to the beekeeping industry of WA.

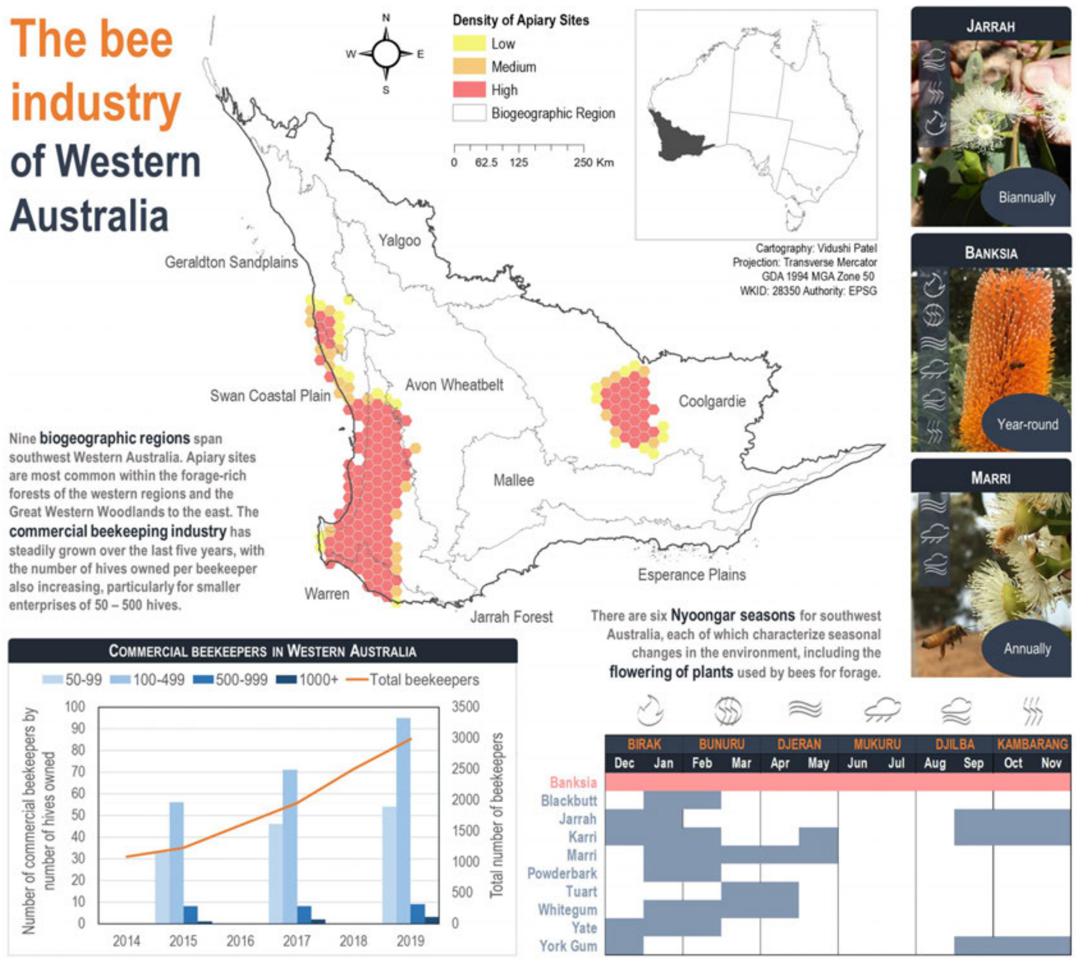
METHODS

Study location: Western Australia

The beekeeping industry of WA is characterized by clean and healthy colonies of the European honeybee (*Apis mellifera*), devoid of the pests and diseases that affect bee health in nearly all other parts of the world (Chapman et al. 2008, Gordon et al. 2014). Although the European honeybee is an introduced species in WA[2], the beekeeping industry relies on native flora, especially eucalypt species, across a mosaic landscape of forest, woodlands, shrublands, and heathlands (Benecke 2007, Arundel et al. 2016). Australia has a diverse native bee fauna, and concerns have been raised as to whether introduced honeybees may compete with native bees for floral resources and/or nesting sites, or affect reproduction in native plants (Paini and Roberts 2005). A recent global review identified a range of evidence detailing adverse effects of managed bees on native bees (Mallinger et al. 2017), but within Australia there is insufficient evidence available to evaluate whether *Apis mellifera* has broad adverse effects on native bee species' survival or reproduction (Paini 2004, House of Representatives Standing Committee on Primary Industries and Resources 2008, Batley and Hogendoorn 2009). Because the European honeybee has been managed and naturalized in Western Australia for many decades, it is possible that the initial wave of adverse ecological effects has passed undocumented.

The majority of WA's honey-producing landscapes are geographically restricted to the Southwest Australian Floristic

Fig. 1. The bee industry of Western Australia indicates an increasing temporal trend in both the total number of beekeepers and those practicing commercially (beekeepers who own > 50 hives; graph). However, state production is constrained to the Southwest Australian Floristic Region (SWAFR), where there is a high density of permits issued for apiary sites (map). Beekeeping is migratory, following the year-round availability of high quality forage species (chart: species are *Banksia*, or eucalypts from the genera *Eucalyptus* and *Corymbia*), with jarrah, marri, and *Banksia* (photos) the key species targeted by Western Australia beekeepers. There are 60 species of *Banksia* in the southwest region, with varying flowering phenologies; beekeepers rely on *Banksia* species during times when eucalypts are not flowering. Data were sourced from the Department of Biodiversity Conservation and Attractions (apiary sites), Interim Biogeographic Regionalisation for Australia (used to delineate biogeographic regions), Australian Bureau of Statistics (state boundaries), and Bureau of Meteorology (used to identify Noongar flowering calendar).



Region (SWAFR; Smith 1969, Gibbs and Muirhead 1998, Benecke 2007, Roshan et al. 2017). Changes in weather and life-stages of flora and fauna across the region are best characterized using the six seasons described by the traditional custodians of the land, the Noongar (Fig. 1). Specifically, forested areas are sought after for polyfloral and monofloral honey production. In WA, forest and woodland stands dominated by jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) are coveted for monofloral honey production, given higher revenue potential because of the honey's unique flavor, texture, and medicinal properties (Roshan et al. 2017, Soares et al. 2017; Fig. 1).

Apiarists in WA migrate their hives between two to six times per year following the sequence of flowering events across the state (because the timing of peak flowering varies with species and location), traversing a mix of private and leased public sites in the process (Somerville and Nicholson 2005, Gordon et al. 2014). Usage of each site lasts between two weeks and a few months depending on variability in active flowering and nectar production. The success of each migration sequence is dependent on the quality of the individual site accessed (Somerville and Nicholson 2005, Pilati and Prestamburgo 2016). Foraging resources are primarily located on government-managed land, including state forest, national parks, and nature reserves, which together account for more than 75% of the state's honey production (Gibbs and Muirhead 1998, Crooks 2008). Over the past decade, 31% of beekeepers have reported reductions in the use of public land because of restricted site access in response to changing government policies (van Dijk et al. 2016).

The beekeeping industry is growing rapidly in WA. Similar to all livestock owners, beekeepers are required to register with the Department of Primary Industries and Rural Development (DPIRD). According to data sourced from DPIRD, between 2015 and 2019 the total number of registered beekeepers more than doubled, with a 64% increase in commercial beekeeping (defined as more than 50 hives) over the last five years (Fig. 1). Demand for forage sites to host apiaries has also increased responding to industry growth. As of 2018, 4479 site licenses were made available by the Department of Biodiversity Conservation and Attractions (DBCA), and of these, 70% were located within the SWAFR (Fig. 1).

Although sites on private land are often used for free or in exchange for honey products, sites on public land require the issue of a lease (subject to renewal every seven years) and vegetation clearing approvals (if clearing is required). Beekeepers request a permit from DBCA to site their apiaries. The requested site coordinates are then sent to the relevant local government for assessment against a series of criteria before sanctioning an apiary permit for hive placement within 500 m from the approved coordinates. Reporting the duration of site use to DBCA is mandatory for monitoring resource use. Spatial overlap of apiary permits with other land tenure may result in additional negotiation with existing lease owners (Salvin 2015), which adds a multifunctional aspect to resource management for beekeeping.

In addition to managing resource access, the beekeeping industry is facing numerous challenges. There is an increasing risk of pest and disease attacks (Crooks 2008, Phillips 2014) despite strict biosecurity regulations. Extensive agriculture and urbanization have resulted in the removal of nearly 80% of the extent of native vegetation in southwest WA since 1910 (Phillips et al. 2010, Andrich and Imberger 2013, Shedley et al. 2018). Land clearing has likely contributed to reduced precipitation (Pitman et al. 2004, Andrich and Imberger 2013) and altered groundwater levels (Dawes et al. 2012), which have adversely affected the biodiversity of the region (Brouwers et al. 2013, Mastrantonis et al. 2019). The declining trend in precipitation since 1970 is projected to continue into the future (Hughes 2011, Smith and Power 2014, Pettit et al. 2015), which has implications for survival and distribution of forage resources. For example, drought can have an adverse impact on the growth and flowering of melliferous (nectar-producing) flora (Benecke 2007). Soil-borne *Phytophthora* dieback is affecting important species used to produce honey, such as karri (*Eucalyptus diversicolor*) and jarrah (Benecke 2007). And last, changing land regulations such as an increase in conservation areas has affected beekeepers' access to their traditional resource base (Benecke 2007).

Given these collective challenges, there are many necessary critical management and governance considerations to ensure the long-term viability of the ecosystem services obtained from beekeeping activities while conserving broader biodiversity. Characterizing the WA beekeeping industry using Ostrom's SESF is a step toward providing a more informed bee-human structural framing to support collective action (Phillips 2014) and a transition toward strategic environmental decision making (McGinnis and Ostrom 2014, Elsawah et al. 2015, Partelow et al. 2019).

Employing the SESF for the beekeeping industry

Identifying and defining important SESF variables and feedback amongst variables required a mixed-methods approach. We conducted qualitative research following a diagnostic procedure suggested by the SESF literature (Ostrom and Cox 2010, Hinkel et al. 2015, Partelow et al. 2018*a*) to prepare an initial list of second tier variables that built upon the first tier concepts (Fig. 2) for the beekeeping SES. Although literature to guide the variable development process was scant (Partelow et al. 2018*b*), sufficient information from other applications of the framework was available to guide direction of the SESF for establishing multitier variables (Ostrom 2009, McGinnis and Ostrom 2014, Delgado-Serrano and Ramos 2015, Vogt et al. 2015), build ontology for new concepts (Frey and Cox 2015), and apply to the bee-human system (Nagendra and Ostrom 2014, Acosta et al. 2018, Partelow et al. 2018*b*, Johnson et al. 2019, Ovitz and Johnson 2019). The initial literature-informed list was further refined and updated to include third and fourth tier variables, and subsequently validated using various local stakeholder engagement activities. For each phase of data collection, key SESF literature including McGinnis and Ostrom (2014), Delgado-Serrano and Ramos (2015), Hinkel et al. (2015), Vogt et al. (2015), and Partelow (2018) was used to guide the collation and refinement of SESF variables. Further details on references and methods for each SESF variable which was ultimately defined are provided in Appendix 1.

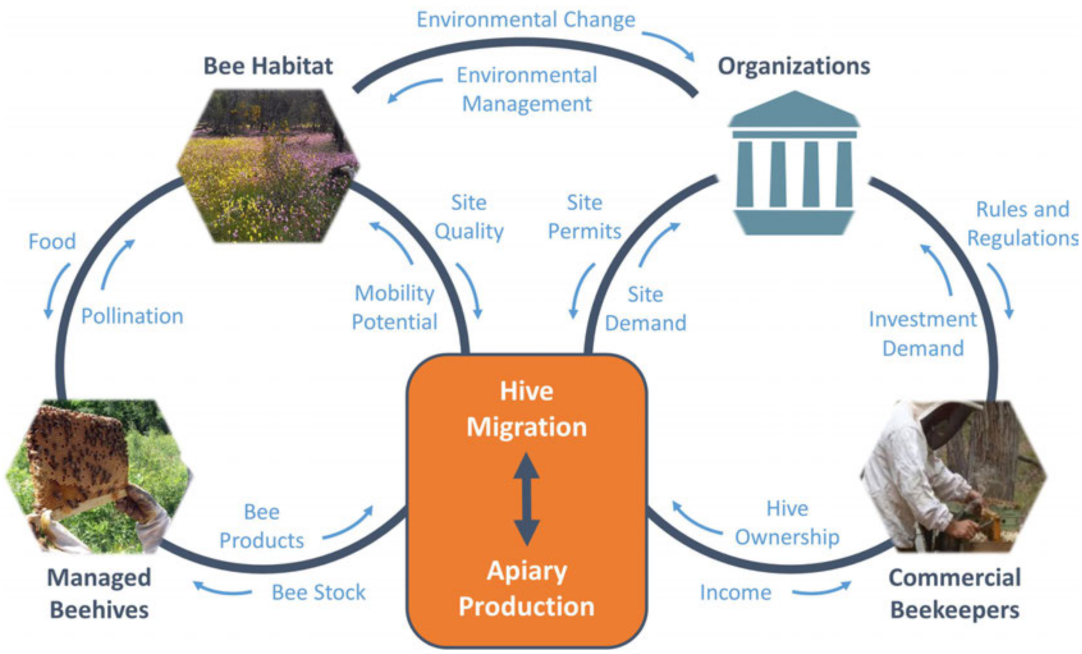
Preparing the initial list of variables

To prepare the initial list of variables, a desktop analysis of government reports, news articles, policy documents, and relevant industry communications was conducted and key terms were listed under each first tier concept. For example, tree plantation, native forest, and weeds on roadsides were listed under "Resource System" from government reports on commercial beekeeping in Australia (Benecke 2007, Goodman 2014). Similar to Phillips (2014), participant observation, collected through attendance at meetings of beekeeping organizations, conferences, and industry-organized community engagement activities, was used to list additional terms under each concept. Archival and observational assessment information was then cross-referenced with other applications of the SESF applications such as fisheries (Basurto et al. 2013, Leslie et al. 2015) and aquaculture (Partelow et al. 2018*b*) so that the listed terms could be identified as an existing variable or a new variable. To refine the variable list, semistructured interviews with key industry stakeholders were conducted. Verification of variables was then performed with industry experts within a focus group discussion session. Following verification, variables were independently validated by expert retired beekeepers within a focus group discussion session. This process of variable refinement, verification, and validation followed a multimethod iterative stakeholder engagement approach (outlined in Table 1), similar to that used by Johnson et al. (2019).

Refinement of the initial list of variables

For variable refinement using semistructured interviews with key industry stakeholders, participants were recruited using a snowballing technique centered on circulation of a volunteer

Fig. 2. Conceptual diagram of the social-ecological system for the beekeeping industry guided by Ostrom (2009). This illustrates the Tier 1 components of the social-ecological system framework, comprising bee habitat (resource system), managed hives (resource unit), organizations (governance system), commercial beekeepers (actors), hive migration (interactions), and apiary production (outcomes).



request flyer via social media, word of mouth, and through advertisement by the Beekeeping Industry Council of Western Australia (BICWA). Using a similar approach to Malkamäki et al. (2016), two question guides were developed, reflecting the broad themes identified through the initial variable preparation process (Appendix 2), and used to conduct semistructured interviews (duration: 35–50 minutes) during 2017 and 2018 with 29 commercial and semicommercial beekeepers. This participant sample represents approximately one-fifth of the beekeeping industry in WA[3] who are major contributors to the total honey production of the state. Sampling was stopped upon saturation where no additional information was collected from participants. Two representatives from governing organizations were also interviewed. All 31 participants provided written consent for undertaking the interviews.

Verification of refined variables

Experts actively engaged with the beekeeping industry in WA were asked to form part of an advisory group[4]. An open-ended discussion session was conducted with the advisory group members regarding the initial and refined lists of variables. Different approaches for open-ended discussion were used because of time commitments of the members; four members met with the lead researcher together in a group setting, and the remaining two members met with the lead researcher individually (during October 2018).

Validation of variables and identification of key feedback within the system

Because experienced beekeepers hold deep local knowledge of bee systems (Galbraith et al. 2017, Uchiyama et al. 2017), a full-day workshop was conducted with six retired beekeepers (December 2018; Fig. 3), whose involvement in beekeeping spanned 30 to 60 years, to undertake independent validation of the verified SESF (Stojanovic et al. 2016; note, active commercial beekeepers with similar experience were unable to commit for the day-long workshop). This validation stage was independent because no leading information was provided to participants. A professional moderator was used to mediate the activities to avoid researcher bias in the process (Knapp et al. 2011). The first activity of the workshop required participants to list all environmental and human aspects deemed necessary to the functionality of the beekeeping industry. Subsequently a mind mapping exercise was perform to harness key interconnectivities across the industry. To refine the initial mind map further, discussion was prompted using 30 keyword cards covering broad SESF themes (e.g., "plants"); this was to ensure participants had considered all the system components for which validation was required. Any discussion by participants concerning system pressures was listed throughout the workshop by a second session moderator who did not engage in the workshop adjudication (this was the lead investigator). Following the mind map generation, the lead moderator then requested participants to add any system pressures that had been noted by the second moderator to the system mind map; an open discussion then refined these ideas. After all four activities were completed, participants were invited to ask questions to the lead investigator and lead moderator regarding the broader objectives of the research.

Based on this iterative data collection process, variables were identified to provide a foundation for applying the SESF to the beekeeping industry. The system variables and interconnectivities

Table 1. Summary of methods used to seek information from stakeholder groups to inform the development of a social-ecological systems framework (SESF) for the beekeeping industry in Western Australia.

Stakeholder group	Number of participants	Method used	Duration	Outcome
Full-time beekeeper	14	Semistructured interviews	35–40 minutes	Refinement of initial SESF variable list
Part-time beekeeper	15			
Government officials	2	Semistructured interviews	30–35 minutes	Refinement of initial SESF variable list
Research experts actively working on vivid aspects of the bee industry	4	Open-ended discussion	2.5 hours	Verification of the refined SESF variable list relevant to the bee industry
Retired beekeepers	6	Workshop Mind mapping	5 hours	Independent validation of the SESF variable list relevant to the bee industry Identification of key feedbacks within the bee industry-SES Identification of key pressures and their potential effect on the bee industry-SES

presented below provide a narrative for the beekeeping industry in WA. As a first step in conceptualizing the beekeeping system as an SESF, a qualitative approach was ultimately adopted for this research.

Fig. 3. Retired beekeepers sharing their knowledge in the mind mapping session for validating social-ecological systems framework variables for the beekeeping industry. Green sticky notes were used to list environmental aspects, yellow for human aspects, and blue for key pressures.

RESULTS

In total 168 SESF variables for the WA beekeeping industry were identified, including 56 second tier, 72 third tier, and 32 fourth tier components (Fig. 4, Appendix 1). Further details on each of the SESF components are provided in the following sections.

Core subsystems

The core subsystems (Tier 1 variables) of the WA beekeeping industry included the Resource System (RS), Resource Units (RU), Actors (A), and Governance System (GS), as described following the variable list provided in McGinnis and Ostrom (2014; Fig. 2). Below we outline some of the first, second, third, and fourth tier variables to provide a narrative to support Figure 4 and the complete list in Appendix 1.

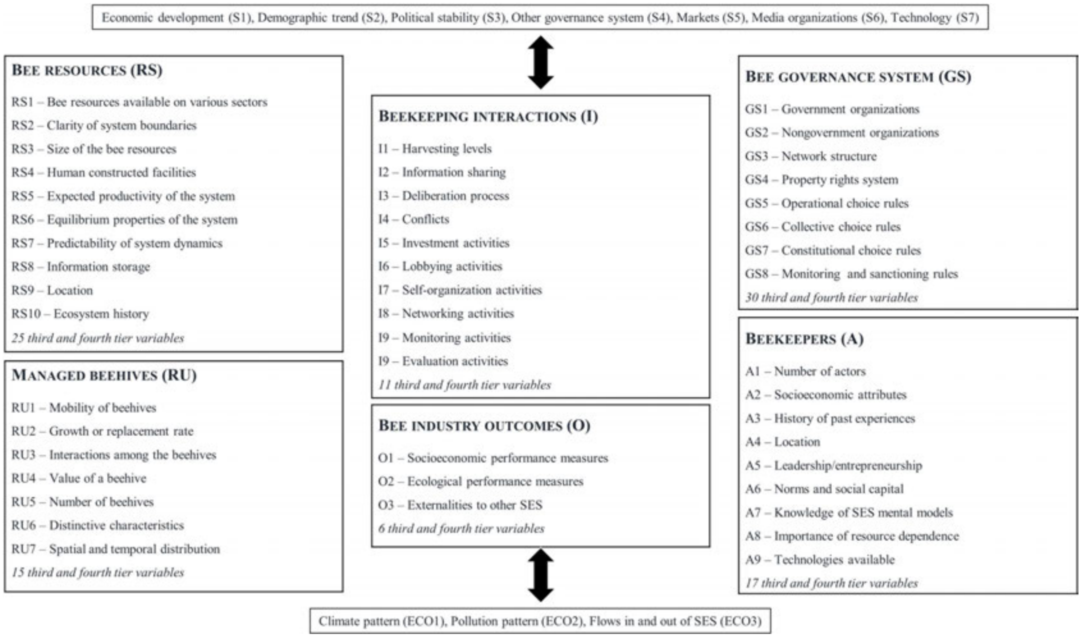
Resource System (RS)

The landscape of bee resources (melliferous flora) forms the resource system for the beekeeping SES. Bee visitation of flora in various land uses such as forest (RS1a), agriculture (RS1b), or other plantations (RS1c) exhibit variable outcomes and access regulations. Setting apiaries within the forest boundary (RS2a) requires the maintenance of 3 km separation distance from other apiaries (RS2c). However, inapplicability of this mandate on private land across fence boundaries (RS2b) further highlights the position of human-constructed facilities (RS4) in accessing resources. Beekeepers have reported determining productivity of the forage landscape (RS5) according to spatial and seasonal variability of flowering events (RS7), location and association (RS9) of species, and information related to previous system disturbances (RS8). For instance, landscapes with high diversity forage species are reported to have longer flowering events, leading to healthy bees and higher yield with less travel. Additional RS variables at second and third tiers, as proposed by Vogt et al. (2015), include ecosystem histories (RS10) specific to natural disasters (RS10a) such as drought or bushfire (RS10b), and were included in the initial list and validated during the variable refinement process.

Resource Unit (RU)

Following the diagnostic questionnaire proposed by Hinkel et al. (2015), the Resource Unit (RU) is identified as the managed bee colony because it is involved in the generation of benefits from the SES and depends on the RS to survive and thrive. Mobility of beehives (RU1) is critical in migratory beekeeping where maintaining healthy and productive colonies (RU2) is the prime interest of the beekeepers (Pilati and Prestamburgo 2016, Pilati and Fontana 2018). Beehives are managed for honey production (RU5a) and for crop pollination (RU5b). Based on the total number of hives managed by a beekeeper, a load (approximately 100 hives can be transported by one flatbed truck) of hives (RU5ai) was added as a fourth tier variable. Load size and their spatial and temporal placement (RU7) depend on forage availability; for example, insufficient forage availability could result in splitting a load into smaller sizes (30–50 hives) but increases transport costs to accommodate their spatial-temporal arrangement. The value of beehives (RU4) was categorized as a market value (RU4a), environmental value (RU4b), and strategic

Fig. 4. First and second tier social-ecological systems framework (SESF) variables that define the beekeeping industry in Western Australia. Third and fourth tier variables are provided in Appendix 1.



value (RU4c; Delgado-Serrano and Ramos 2015). The condition of the RS and RU are the most important factors contributing to social-ecological system sustainability (Frey 2016), and inter/intraspecific interactions (RU3a/RU3b), including spatial proximity (RU3ai) of the resource units. Marking each hive (RU6a) with a registered brand is mandatory for all beekeepers in WA.

Governance system (GS)
Government organizations (GS1) that manage and monitor bee resources, e.g., DBCA, and bee stock, e.g., DPIRD, directly interact with beekeepers and operational activities at state-level organizations (GS1b) as well as the local government-level (GS1c). Contributions from research organizations (GS2b) were found to improve the beekeeping industry with 74% of beekeepers in Australia experiencing up to 25% increase in production by changing their management practices as a result of research (van Dijk et al. 2016). Based on sectoral research funding, fourth tier SESF variables were added for academic research (GS2bi), industry-funded research (GS2bii), and cooperative research centers (GS2biii). Social connections between beekeepers and land owners/managers (GS3a) and within beekeeper groups (GS3ai) are a key influencing factor regarding resource access and use, irrespective of the governing rules (GS5-7) because of an increasing reliance on private land. Conflict between beekeepers (I4a) can also be related to GS3a and GS3ai, as identified by several apiarists. In addition, constitutions related to beekeeping (GS7a), biosecurity (GS7b), access to resources (GS7c) including forest management (GS7cii), local government bylaws (GS7ciii), and food handling requirements (GS7civ) influence monitoring and sanctioning rules (GS8a-b) at a local level, and were added as fourth tier variables.

Actors (A)
Migratory beekeepers are the key actors (A) in the bee-human system. Age and intergenerational involvement in beekeeping are key demographic attributes (Phillips 2014, Galbraith et al. 2017) that determine experience (A3) and local ecological knowledge (A7a). Based on diverse economic characteristics (A2b), four fourth tier SESF variables were identified: large-scale operators (> 499 hives; A2bi), small-scale operators (50–499 hives; A2bii), equipment manufacturers/suppliers (A2biii), honey packers, and queen bee breeders (A2biv). All large-scale operators were full-time beekeepers (A8a) with total dependence on beekeeping for their livelihoods. Intergenerational beekeepers followed the knowledge of their parents and grandparents regarding the rich spatial-temporal history of resources, production, weather, and issues at their regular forage sites, and were also involved in sharing beekeeping knowledge by training new beekeepers (A5b). For other commercial and semicommercial beekeepers, a general transition of hobbyists from part-time (A8b) to full-time (A8a) beekeeping was observed. Various levels of technology (A9) were reported including mobile phone and internet to access information, and use of satellite imagery and other advanced sensor-based devices for hive resource monitoring; these were dependent upon the scale of operation, age of the beekeeper, and aspiration for future expansion.

Focal action situation: Key Interactions (I) and Outcomes (O)
Information sharing (I2) concerning forage resources was reported as a main form of interaction between beekeepers. The state-level beekeeping organization (BICWA) is involved in deliberation (I3) and investment activities (I5) for the industry and has representatives from formal beekeeper groups (I2a) including hobbyists (WA apiarist society), semicommercial and commercial (WA beekeeper association, WA farmer federation),

and the committee of producers (Agriculture Produce Commission). Additionally, there are known informal beekeeper groups (I2b) with various levels of interaction.

Several conflicts were included as SESF variables because they were identified by the majority of participants as affecting governance of the bee-human system. Conflict between beekeepers (I4a) can arise where one beekeeper is seen to harvest resources from another beekeeper's patch; generally by placing hives on the edge of private land next to forest. Such situations may unfold due to noncompliance of the 3 km apiary separation regulation on private land (RS2c). Close colony proximity can also inadvertently increase biosecurity risk through compromised hive health (e.g., disease transmission), potentially leading to a loss of hives. In addition, loss of bees due to use of fungicide by a farmer hiring beehives for pollination services was also identified as a point of contention (I4b). Conflict also exists between regulatory authorities, e.g., DBCA, and beekeepers regarding loss of forage resources due to land management practices, such as prescribed burning (I4c).

Harvests vary by beekeeper (I1a) and depend on the number of hive holdings, knowledge, and access to forage resources and other socioeconomic attributes. Different forage locations (I1b) lead to variability in yield (quantity) and quality as a result of vegetation mix and health. Resource monitoring activities (I9a) carried out by beekeepers are based on monitoring rules (GS8) developed by government organizations (GS1) and influence hive migration patterns and expected productivity of forage sites (RS5). However, decision making for migration of beehives also depends on the growth and replacement rate (RU2) of the hives, hence, beehive monitoring activities (I9b) was added as a variable under monitoring activities.

When beekeepers do not receive payment for pollination, it is considered an externality (O3ai) of the system flowing to agriculture and forest systems alike (Siebert 1980, IPBES 2016). Combining beekeeping with other industries, e.g., api-tourism in Slovenia, can have multiplier effects on regional economies and support improved management (Gemeda 2014, Arih and Korošec 2015). Packaging industries (O3aii) was added as a positive externality. Resource competition with other species (O3bi) and potential for disease transmission (O3bii) through migratory practices was identified as a negative externality (O3b). Interaction between bees and beekeepers (I9b) is integral to beekeeping activities and affects overall beehive migration patterns. For example, beekeepers managing a large number of hives tend to visit a number of sites across the state, and move greater distances from their home location, when compared to a small-scale, part-time beekeepers.

Sustainability pressures

Key pressures that affect the sustainability of the WA bee-human system were identified. Responses to interview questions related to issues and pressures (see Appendix 2) with beekeepers and government representatives were analyzed to calculate how many participants mentioned each pressure (see Table 2). All listed pressures were independently validated by the retired beekeepers group except for "backward in technology usage." The three top pressures mentioned by stakeholders were (i) availability, access, and utilization of apiary sites, (ii) burning of forage resources, and (iii) climate change. These pressures were mentioned by the majority of interviewees and focus group participants and received consensus in all stakeholder engagements (see Table 2).

Table 2. Pressures on the Western Australia bee-human system according to the number of people in each stakeholder group who mentioned each pressure. Retired beekeepers independently validated pressures during a collective workshop, hence their responses are noted as a binary yes-no.

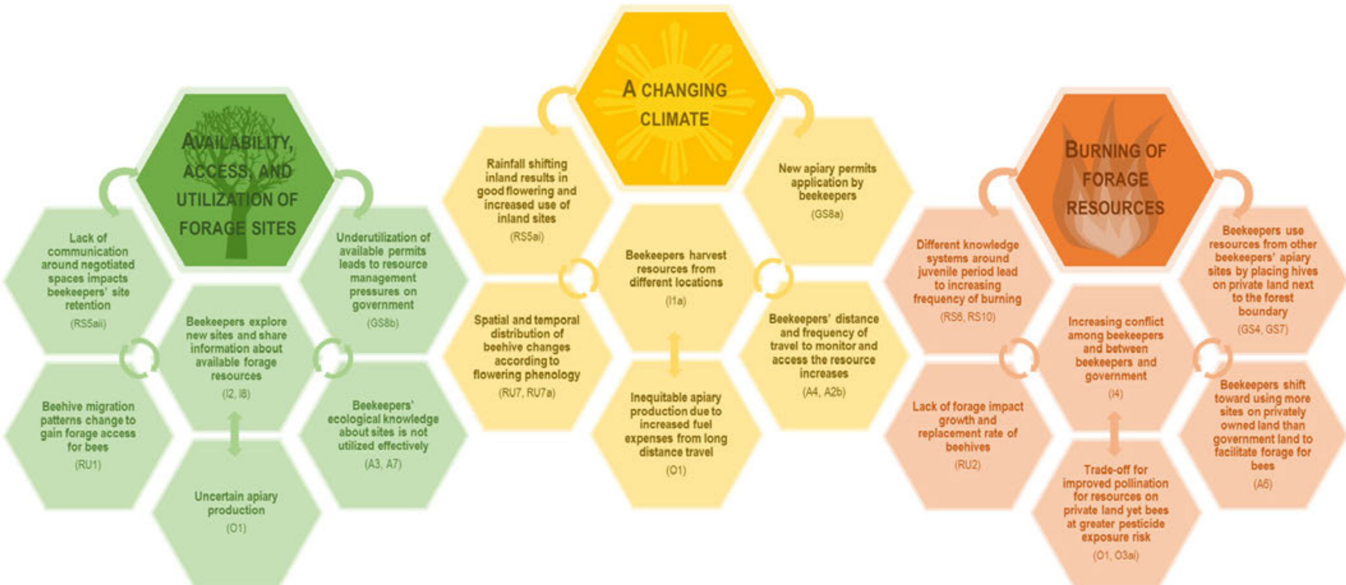
Pressure	Beekeepers (n = 29)	Government representatives (n = 2)	Retired beekeepers (n = 6)
Availability/access to forage sites	18	1	√
Burning of forage resources	17	1	√
Climate change	12	1	√
Lack of rainfall and/or declining water table	10	0	√
Land use / land cover change	9	0	√
Biosecurity	8	2	√
Logging	4	0	√
Underutilization of sites	3	1	√
Variability in flowering	3	1	√
Government (in)action	3	0	√
Hive theft and vandalism	2	0	√
Spraying of fungicides and insecticides	2	0	√
Lack of communication	2	1	√
Cheap honey	1	0	√
Backward in technology usage	1	0	
Lack of authority to monitor sites	1	2	√

DISCUSSION

Global bee decline and its likely consequences for human well-being are increasingly being recognized (Gill et al. 2016, Potts et al. 2016, Klein et al. 2018). A multitude of natural and anthropogenic factors have been attributed to this decline, including depletion of forage resources (Goulson et al. 2015, Durant 2019). Although forage scarcity results from both natural (e.g., phenological mismatch) and anthropogenic (e.g., land use change) factors, effects of forage scarcity is detrimental to all bee populations and could potentially contribute to resource competition between wild and managed bees. A clearer understanding of bee-human systems can provide a potential pathway to better manage ecosystem services delivered by managed bees (Gill et al. 2016, Potts et al. 2016, Matias et al. 2017, Klein et al. 2018, Patel et al. 2020).

We have described the first application of the SESF to the beekeeping sector, enabling us to understand the structural interconnectivities within the beekeeping SES and the challenges that threaten the sustainability of the system. Decision makers can use our SESF to direct management operations for minimizing trade-offs and maximizing synergies for system components to work toward optimized system functionality. We provide insights to illustrate potential use of our SESF by showcasing three examples that relate to the top three system pressures identified during the data collection process. The SESF can provide a structured response mechanism for enhancing environmental management of the beekeeping industry and guide sustainable decision making for managing system pressures, including those that are under immediate control of state policy

Fig. 5. Priority pressures of (i) availability, access and utilization of forage sties, (ii) a changing climate, and (iii) burning of forage resources. Each diagram indicates the impact of the pressure on various components and example feedback pathways within the beekeeping social-ecological system (SES) in Western Australia (refer to Appendix 1 for variable coding). The diagrams are formatted to match the SES framework core components illustrated in Figure 2.



makers, e.g., forage access or burning of resources, and also those that require long-term systematic change, e.g., climate change or rainfall shifts.

Addressing priority bee-human system pressures

Changes affecting bee-human systems are generally socio-cultural, environmental, economic, and governance-oriented in nature (Matias et al. 2017). Sustainability of the beekeeping industry depends on continuous access of quality forage sites (Pilati and Prestamburgo 2016). Challenges such as decreasing resource access and biosecurity risks have been previously documented for the Australian beekeeping industry (Phillips 2014), and reinforced through our data collection. To address key pressures using the SESF, interconnectivities where synergies and trade-offs occur are illustrated in Figure 5. This provides insights into the elements and feedback processes contributing to the top three pressures (discussed in the following section) identified for the WA beekeeping industry.

Availability, access, and utilization of apiary sites

In migratory beekeeping, sustainability varies according to the sequence of apiary sites accessed by a beekeeper (Pilati and Prestamburgo 2016). Beekeepers' access to forage sites depends on a range of factors including biophysical conditions (e.g., blocked physical access due to vegetation growth), legislation (e.g., burning regimes), negotiations (e.g., with land owner or existing lease holder), changing land management practices (e.g., approval of new walking trails; RS5ai), and change in individual practice (e.g., upgrading truck size limits access to sites only accessible with smaller vehicles). The importance of forage locations with high species diversity (Coh-Martínez et al. 2019) and increasing variability in flowering events cause full-time beekeepers to maintain a number of underused sites as backup (Fig. 5). In addition, technological progress in management initiatives also contributes to variability in SESs; for example, in WA, an online portal designed to ease the apiary permit process has been attributed to increasing vandalism and hive-theft after apiary site locations were made available online.

A national level policy change can also add to SES variability. For example, revising the regulation of holding permits per number of hives, under the National Competition Legislation (CALM 1997), has resulted in conflict among beekeepers because of withholding apiary permits for earning rent rather than providing forage. This underuse of resources (Mauerhofer et al. 2018, Miyanaga and Shimada 2018) requires beekeepers to find new sites, and change hive migration patterns (RU1), leading to uncertain apiary production (O1). Such situations can result in increased resource management pressure on the government (GS8b). In addition, conservation initiatives, aimed at limiting the interactions of managed bees with natural ecosystems, can also affect a beekeeper's access to resources. The issue of availability and access to resources largely contributes to SES sustainability (Frey 2016) and requires an understanding of the nonlinear nature of SES interactions in order to avoid siloed decisions. Key variables and interactions identified in this research provide the basis to guide integrated decisions toward sustainable resource access for bee-human systems.

A changing climate

Beekeeping activities are heavily influenced by climatic conditions, including rainfall and temperature. A positive correlation between rainfall and winter survival of bee colonies (Switanek et al. 2017) and honey harvest (Delgado et al. 2012) has been noted in the literature. Rainfall patterns are regularly observed by beekeepers for predicting flowering events. The juvenile period of bee forage species varies geographically and is also connected with variations in rainfall (Burrows et al. 2008, Bradshaw et al. 2018, Shedley et al. 2018). Terms such as "patchy flowering," "uneven production," and "consistently random flowering" were used by beekeepers to describe climate effects on the resource system. In addition, lack of nectar, thinning of nectar, and bitter nectar were reported and associated with climate change.

A relationship between rainfall patterns and flowering events (and nectar production) is evident with increasing use of inland forage sites (toward Coolgardie: Fig. 1) to access good flowering events, i.e., a hive filled with honey within two weeks, resulting from increasingly variable precipitation. Rainfall shifts toward inland areas are supporting beekeepers with additional forage sites (RS5ai) but may lead to inequitable production (O1) because of fuel intensive, long-distance travel involved with accessing more remote locations. In addition, our SESF analysis has revealed impacts on other parts of the SES. For example, unpredictable flowering also escalates beekeepers' travel expenditure because of additional site visits to confirm resource availability prior to utilization (A4, A2b; Fig. 5).

Burning of forage resources

Beekeepers understand fire in great detail, including frequency, intensity, and extent of disturbance. Forage species in the Mediterranean-type climates have naturally adapted to fires, however a species' response during the juvenile period—capacity of species to produce flowers and nectar—varies and depends on the frequency and intensity of burning (Bradshaw et al. 2018, Shedley et al. 2018). For instance, as cited in Bradshaw et al. (2018), *Banksia sessilis* takes 12–15 years postfire to reach maximum honey production, and frequent burns can result in loss of the species. In the SWAFR, almost 180,000 ha is burnt annually by DBCA to manage fuel load and avoid catastrophic fire events (Bradshaw et al. 2018). An association between burning and underutilization of sites is evident from beekeepers' statements such as "All our products go to smoke," "Parrot bush [*Banksia sessilis*] is completely lost to frequent burning at the coast," and "We use more private sites now government sites are not reliable - it's frequently burnt" (GS4,GS7).

Reducing harvesting levels or a complete loss of crop (nectar-bearing flowers) due to frequency, intensity, and timing (during budding season) of prescribed burns was noted as the main cause of conflict between beekeepers and government organizations (I4; Fig. 5). We identified contradictory views regarding recovery of species after burning between government officials and beekeepers (RS6, RS10). This represents a critical gap between two knowledge systems and a challenge of integrating beekeepers' practical knowledge obtained through regular monitoring of flora with land management practices.

Understanding structural interconnectivities

Aligning management decisions to the complex, spatially explicit dynamics associated with human and ecological systems is vital in addressing sustainability issues and effective spatial planning in a SES (Leslie et al. 2015, Ovitz and Johnson 2019). The multiscale, multidirectional applicability of our SESF provides opportunity to understand complex interconnectivities leading to these SES dynamics within the beekeeing industry. Understanding the structural interconnectivities of the beekeeping system through SESF mapping has revealed impacts on other parts of the SES that may not have been initially obvious. For example, a preference by beekeepers to access resources closer to their home location, i.e., close to urban and peri-urban areas to save the time and costs involved in hive-transportation, can lead to increased intensity of resource use and high competitiveness within close proximity to urban, peri-urban systems. Research findings indicate that migration decisions by beekeepers reflect self-organization within the beekeeping SES, with part-time beekeepers preferring to migrate hives within a couple of hundred kilometers from their home location, whereas full-time (mostly family) beekeepers are willing to migrate hives longer distances to access forage resources.

The importance of integrating local ecological knowledge with local management practices in SES is also highlighted in our research (Maderson and Wynne-Jones 2016, Uchiyama et al. 2017, Colding and Barthel 2019, Hill et al. 2019) through the identification of third and fourth tier variables aided by multigenerational beekeepers. Through considering the spatially explicit nature of social-ecological interactions, collective action involving local actors and the government may result in more effective spatial planning for the industry (Nagendra and Ostrom 2014, Leslie et al. 2015, Dressel et al. 2018, Partelow et al. 2018*a*). For instance, beekeepers' local knowledge can be used to adjust burning regimes and schedules to avoid burning flora during budding or nectar flow.

CONCLUSION

In this paper we have presented the first application of Ostrom's SESF to understand structural interconnectivities within the beekeeping industry. We combined various qualitative research methods to identify important social and ecological components of the bee-human system and their interconnectivities. We also identified and discussed key social-ecological pressures to the beekeeping industry, highlighting the need for integrated decision making and incorporation of local ecological knowledge in management decisions. As such, our SESF assessment can be used to facilitate multidirectional communication and knowledge exchange between beekeeping industry actors to address stakeholder needs, particularly for the improved management of common pooled resources. Additionally, the framework can be used to inform integrated policy design in order to sustain apiary production while safeguarding bee-diversity and associated ecosystem services. Although certain lower tier variables, e.g., apiary permits (GS8ai), proximity of resource units (RU3ai), and load size (RU5ai), are unavoidably specific to the WA system, the diagnosis presented here can guide sustainable management decision making associated with other bee-human systems including wild bee conservation and nonmigratory beekeeping, as well as migratory beekeeping in alternative geographical locations. For example, conflicts arising from competition over Manuka resources in New Zealand (Lloyd 2017) could be managed using our SESF given the transferability of first and second tier variables across systems. Our recommendation is to build upon this foundational research to initiate a framework application to quantitatively investigate the outcomes of system interconnectivities (e.g., Leslie et al. 2015, Dressel et al. 2018, Pacilly et al. 2019) within the bee-human system. Such an approach would enable complex social-ecological systems modeling to test the implications of behavioral decision making, such as exploring how factors that govern landscape mobility affect beehive migration and impact system sustainability.

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[1] In this paper, we use the word "bee" as shorthand to refer to the European honeybee, *Apis mellifera*. We recognize that there are approximately 20,000 described species of bee, of which 50 are managed species, the honeybee being one of them.
[2] Acknowledging that the European honeybee is a non-native species in Western Australia, in this paper we consider only managed honeybee colonies and do not consider feral honeybees. Feral bees have a suite of associated conservation issues including taking over suitable nesting hollows for native birds, mammals, and reptiles (Gibbons and Lindenmeyer 2002, Johnstone et al. 2013).
[3] In this paper we define the beekeeping industry to represent commercial (apiarists managing more than 500 hives) and semicommercial beekeepers (apiarists managing between 50 and 500 hives) in WA.
[4] Five members were selected to form the advisory group based on an individual's reputation within the beekeeping industry and ensuring a diverse representation of stakeholder groups, which included government agencies, private businesses, research institutions, and beekeeping organizations.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/11639

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Data Availability Statement:

The aggregated data that support the findings of this study are included within the publication as an appendix. The raw data are not publicly available because of ethical restrictions around maintaining anonymity of research participants.

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Appendix 1: SESF variables for beekeeping SES are listed with their definitions and methods used to identify them.

Sources are listed if variable is found in published or unpublished literature. Note that both, SESF guiding literature and literature looking at bee systems explored to identify variables. In addition to literature, online sources such as government websites, rules and regulations had also supported variable identification process,

SESF variable for beekeeping industry (Focal SES)	Definition/Description	Tier	Method†				Sources ‡
			L	I	O	W	
Governance System (GS)	Bee governance system	1	√	√	√	√	9, 11
Government organization (GS1)	Government organizations managing and monitoring action situation for beekeeping industry system	2	√	√	√	√	2, 9, 11, 12
National level government organization (GS1a)	Federal government	3	√	√	√	√	2
State level government organizations (GS1b)	State government	3	√	√	√	√	2
Local Government (GS1c)	Local government	3		√		√	
Non-government org (GS2)	Presence of non- government organization managing and monitoring action situation for beekeeping industry system	2	√	√	√	√	2, 9, 11, 12
Industry organizations (GS2a)	Industry owned and operated organizations that collectively represent various beekeepers associations (e.g. BICWA)	3		√	√	√	
Beekeepers associations (GS2ai)	Presence of various beekeepers associations such as commercial, semi-commercial and hobby beekeepers associations	4		√		√	
Queen breeders (GS2aii)	Queen bee breeders group that rears and provides queen bees to the state due to closed borders	4		√	√	√	
Industry leaders (GS2aiii)	Leading WA beekeepers who are positioned at industry organizations, involved in lobbying activities, brings investment for the development of the industry, provide	4				√	

	knowledge about resources and beekeeping techniques to new beekeepers						
Research organizations (GS2b)	Organizations actively engaged in research related to various aspects of the beekeeping industry	3	√	√	√	√	17
University research (GS2bi)	Student and researchers from universities involved in the research beneficial to the beekeeping industry	4		√		√	
Industry funded research (GS2bii)	Research funded by industry owned and operated organizations (targets industry specific issues, beekeeper researchers)	4		√		√	
Cooperative Research centres (CRCs)	Collaborative research involvement from government, non-government organizations (e.g. CRC for honeybee products)	4		√	√	√	
Network Structure (GS3)	Social or political connections among government / no-government organizations, beekeepers and other industry stakeholders.	2	√	√	√	√	2, 9, 11, 12
Social network (GS3a)	Social connections between beekeepers and government or private land owners/managers	3	√	√	√	√	2
Informal beekeeper groups (GS3ai)	Information flows among groups of beekeepers (e.g. information regarding resource availability and access)	4		√		√	
Market network (GS3b)	Presence or absences of multilevel of market structure and associated interactions	3		√			
Local farmers' market (GS3bi)	Regular or occasional local markets and fresh food produce outlets	4		√		√	
Supermarkets (GS3bii)	Supermarket networks	4		√		√	
Export market (GS3biii)	Export market and associated interactions	4		√	√	√	
Property rights systems (GS4)	Presence of property rights system governing access to forage resources (e.g. private property, common property, restricted access)	2	√	√	√	√	2, 9, 11, 12
Operational choice rules (GS5)	Presence of formal written rules for access and/or harvesting from the forage resources	2	√	√	√	√	2, 9, 11, 12
Collective choice rules (GS6)	Rules defined by involved stakeholders following their understanding of local social, ecological and political conditions	2	√		√	√	2, 9, 11, 12
Constitutional choice rules (GS7)	Law, act or mandates defined by regional or national level government	2	√	√	√	√	2, 9, 11, 12
Act relating to beekeeping activity (GS7a)	Biosecurity and Agriculture Management Act 2007	3		√	√	√	19

Act relating to biosecurity (GS7b)	Biosecurity and Agriculture Management Regulation 2013	3		√	√	√	19
Acts relating to access and use of resources (GS7c)	Conservation and land management Act 1984, , Biodiversity Conservation Act 2016 and Biodiversity Conservation Regulations 2018	3	√	√	√	√	22
Conditions for using resources available on Government owned land (GS7ci)	General Conditions for using Apiary Authorities on Crown land in Western Australia	4	√	√	√	√	24
Forest management plans (GS7cii)	Planning for management of forest used for apiary authority	4		√	√	√	20
Local government Acts or Bylaws (GS7ciii)	Verge treatment/spraying , regulations relating to keeping bees in neighbourhood	4		√		√	
Conditions for using resources managed by managers other than government (GS7civ)	Recreation, mining, timber and logging, pastoral leases	4	√	√	√	√	23
Requirements relating to food handling, processing and labelling (GS7d)	Regulation for extraction, processing, packing and labelling of honey	3		√		√	21
Monitoring and sanctioning rules (GS8)	Presence of authority to for resource monitoring and access sanctioning	2	√	√	√	√	2, 9, 11, 12
Sanctioning rules (GS8a)	Process of sanctioning authority to access the resources	3	√	√	√	√	2
Apiary permits (GS8ai)	Authority to place beehives on forage locations	4	√	√	√	√	16, 26
Clearing permits (GS8aii)	Authority to clear vegetation to gain physical access and place beehives on forage locations	4	√	√	√	√	24
Monitoring rules (GS8b)	Process of monitoring resource availability and usage	3	√	√		√	2
Apiary site monitoring (GS8bi)	Monitoring resource use on apiary authority	4		√		√	
Monitoring beehives (GS8bii)	Monitoring requirement and availability of required resources	4		√		√	
Actors (A)	Beekeepers	1	√	√	√	√	7, 9, 11

Number of actors (A1)	Number of beekeepers	2	√	√	√	√	9, 12
Socio-economic attributes (A2)	Socio-economic characteristics of beekeepers	2	√	√	√	√	2, 9, 11, 12
Demographic attributes (A2a)	Age of beekeepers	3	√	√	√	√	2, 13
Intergenerational beekeeper (A2ai)	Beekeeping generation	4		√	√	√	
Economic attributes (A2b)	Economic characteristic of beekeeper	3	√	√	√	√	2
Large-scale operators (A2bi)	Beekeepers more than 500 hives	4		√	√	√	
Small-scale operators (A2bii)	Beekeeper less than 500 hives	4		√	√	√	
Equipment manufacturer/supplier (A2biii)	Manufacturer / supplier of beekeeping equipment (May or may not be keeping bees)	4		√		√	
Producer, packers and queen bee breeders (A2biv)	Beekeepers involved in honey packing or queen breeding	4		√	√	√	
Social attributes (A2c)	Presence of mutual support, cooperation and leadership quality	3	√	√	√	√	2
History of past experience (A3)	Duration of involvement in beekeeping	2	√	√	√	√	2, 9, 11, 12
Location (A4)	Residential location of beekeepers	2	√	√	√	√	2, 9, 11, 12
Leadership/ Entrepreneurship (A5)	Presence of educated and well-connected leader who is respected by their peers	2	√	√	√	√	2, 9, 11, 12
Volunteer leaders (A5a)	Active beekeeper to lead collective action	3		√	√	√	
Training for beekeeping business (A5b)	Beekeeper involved in providing formal/informal training for new beekeepers	3		√		√	
Norms and social capital (A6)	Closeness of community	2	√	√	√	√	2, 9, 11, 12
Social interaction (A6a)	Interactions and knowledge exchange among beekeepers	3		√		√	
Trust among actors (A6b)	Level of trust among beekeepers	3		√	√	√	
Relationship with other actors (A6c)	Relationship of beekeepers with actors other than the focal SES (e.g. farmers, local residents, consumers)	3		√		√	

Knowledge of SES models (A7)	Presence/ degree of Local ecological knowledge (LEK)	2	√	√	√	√	2, 9, 11, 12
Local knowledge on SES (A7a)	Spatial- temporal knowledge of floral source and understanding of effects of beekeeping activities on local environment	3	√	√	√	√	2, 12
Knowledge of concepts such as conservation, human-nature relationships (A7b)	Presence / degree of understanding of concepts like conservation, ecosystem services and human-nature relationship	3	√	√	√	√	2, 12
Knowledge of the biological shocks on SES (A7c)	Level of knowledge of the potential and real disturbance patterns and its possible effects	3	√	√	√	√	2, 12
Importance of resource (dependence) (A8)	Livelihood dependence on bee resources	2	√	√	√	√	2, 9, 11, 12
Full-time operators (A8a)	Completely depend on beekeeping for livelihood	3		√	√	√	
Part-time operators (A8b)	Has a source of income other than beekeeping	3		√	√	√	
Technologies available (A9)	Technologies used to identify, extract, harvest and manage the resource (A9)	2	√	√	√	√	2, 9, 11, 12
Resource system (RS)	Bee resources - Resources that produce melliferous flora	1	√	√	√	√	7, 9, 11
Sector (RS1)	Bee resources available on various sector (e.g. forest)	2	√	√	√	√	2, 9, 11, 12
Forest flora (RS1a)	Bee resources available from trees and other understorey plants in forest	3	√	√	√	√	7
Agriculture flora (RS1b)	Bee resources available from agriculture crops	3	√	√	√	√	7
Other plantation (RS1c)	Bee resources available from plantation	3	√	√	√	√	7
Revegetation (RS1ci)	Bee resources available from revegetation	4	√	√	√	√	7
Verge plantation (RS1cii)	Bee resources available from plantation on new or existing verge	4	√	√		√	6
Clarity of system boundary (RS2)	Clarity of the system's geographical, social and legal boundaries	2	√	√	√	√	2, 9, 11, 12
Geographic boundaries (RS2a)	Geographic boundary of bee resources	3	√				2
Anthropogenic boundaries (RS2b)	Fences or other human constructed boundaries	3	√	√	√	√	2

Individual's resource access boundary (RS2c)	User-defined boundary for the bee resources	3	√	√	√	√	2, 18
Size of the resource system (RS3)	Spatial extent and its area of bee resources	2	√	√	√	√	2, 9, 11, 12
Area covered by geographic extent of bee resources (RS3a)	Total area for bee resources	3	√	√	√	√	18
Size of different types of ecosystems within the extent of bee resources (RS3b)	Total area for each sector of bee resources	3	√		√		18
Fragmentation dynamics (RS3c)	Frequency of fragmentation over time	3	√		√		18
Human constructed facilities (RS4)	Anthropogenic structures supporting resource access and management	2	√	√	√	√	2, 9, 11, 12
Infrastructure e.g. road, highways (RS4a)	Availability of infrastructure for movement (e.g. roads, access ways) or as impediments (e.g. dams, fence)	3	√	√	√	√	2, 18
Water resources (RS4b)	Proximity to the nearest water resources	3		√		√	
Other facilities (RS4c)	Recreation facilities	3		√		√	
Productivity of the system (RS5)	Estimation about potential productivity of the area	2	√	√	√	√	2, 9, 11, 12
Resource dynamics (RS5a)	Regularity of flowering events	3	√	√	√	√	18
Natural resource dynamics (RS5ai)	Natural availability or unavailability of flowering event e.g. annual, biannual flowering frequency	4		√	√	√	
Resource dynamics in response to human disturbances (RS5aii)	Availability or unavailability of flowering due to man-made changes e.g. flowering event after species recovery from prescribed fire	4		√	√	√	
Resource diversity (RS5b)	Diversity of bee flora species	3	√	√	√	√	1
Equilibrium properties of the system (RS6)	Positive or negative influences on the equilibrium of the bee resources (e.g. seasonality, rainfall trends)	2	√	√	√	√	2, 9, 11, 12
Frequency of disturbances (RS6a)	Frequency of external impacts and system response e.g. frequency of draught/fire events and species recovery	3	√	√	√	√	18
Extent of disturbances (RS6b)	Extent of external impacts and system response e.g. extent of draught/fire events and species recovery	3	√	√	√	√	18

Intensity of disturbances (RS6c)	Intensity of external impacts and system response e.g. Intensity of draught/fire events and species recovery	3	√	√	√	√	18
Predictability of system dynamics (RS7)	Degree to which beekeepers are able to forecast/identify patterns in productivity of bee resources	2	√	√	√	√	2, 9, 11, 12
Probability of driving forces leading to system dynamics (RS7a)	Probability of driving forces e.g. uncertain nature of rainfall or natural fire events	3	√	√	√	√	18
Variability of driving forces leading to system dynamics (RS7b)	Variability of driving force e.g. variation in nectar production	3	√	√	√	√	18
Storage characteristics (RS8)	Information storage regarding effects of disturbances on bee resources	2	√	√	√	√	2, 9, 11, 12
Location and association (RS9)	Spatial configuration and extent of bee flora where system can be accessed by the beekeepers	2	√	√	√	√	2, 9, 11, 12, 18
Ecosystem history (RS10)	History of ecosystem dynamics	2	√	√	√	√	18
History of natural disasters (RS10a)	History of draught or bush fire events	3	√	√	√	√	18
History of anthropogenic use and disturbances (RS10b)	History of prescribe burn events	3	√	√	√	√	18
Resource unit (RU)	Beehives managed by beekeepers	1	√	√	√	√	5, 9, 11
Mobility of Resource units (RU1)	Beehive migration patterns	2	√	√	√	√	2, 9, 11, 12
Stationary Resource units (RU1a)	Stationary (non-migratory) beehives	3	√	√		√	18
Mobile Resource units (RU1b)	Migration patterns of beehives	3	√	√	√	√	9, 11, 18
Growth or replacement rate (RU2)	Absolute or relative descriptions of changes in quantities (x) of beehives over time (t)	2	√	√	√	√	2, 9, 11, 12
Interactions among resource units (RU3)	Interactions among beehives managed by same or different beekeeper	2	√	√	√	√	2, 9, 11, 12
Intraspecific interaction (RU3a)	Resource competition within honeybee species e.g. Hive robbing	3	√	√	√	√	18

Proximity of resource units (RU3ai)	Inter/intra colony distance among beehives	4	√	√		√	10, 24
Interactions damaging resource unit conditions (RU3aii)	Potential for disease transmission	4	√	√		√	10
Interspecific resource competition (RU3b)	Resource competition among nectarivorous species e.g. for nesting or forage resources	3	√	√	√	√	18
Value of resource unit (RU4)	Value of a beehive	2	√	√	√	√	2, 9, 11, 12
Market value (RU4a)	Cost associated with a beehive (e.g. levy, insurance etc.)	3	√	√	√	√	2
Environmental value (RU4b)	Non-monatory value of a beehive (e.g. importance for pollination)	3	√	√	√	√	2
Strategic value (RU4c)	Social/cultural value of a beehive (e.g. importance as a hobby)	3	√	√	√	√	2
Number of units (RU5)	Number of managed hives	2	√	√	√	√	2, 9, 11, 12
Number of units leading to economic benefit (RU5a)	Hives managed for economic benefits	3		√		√	
Load size (RU5ai)	Number of hives managed for honey production	4		√		√	
Number of units leading to economic and environmental benefits (RU5b)	Hives managed for pollination services	3		√		√	
Distinctive characteristics (RU6)	Colouring / numbering of hives aiming identifying individual loads	2	√	√	√	√	2, 9, 11, 12
Distinctive markings (RU6a)	Marking beehives with brand code	3	√	√		√	
Spatial and Temporal distribution (RU7)	Beehive migration patterns	2	√	√	√	√	2, 9, 11, 12
Spatial patchiness (RU7a)	Hive migration on fragmented landscape	3	√	√		√	18
Temporal patchiness (RU7b)	Hive migration following phenology and patchy flowering	3	√	√		√	18
Interactions (I)	Key activities and processes in beekeeping	1	√	√	√	√	9, 11
Harvesting (I1)	Quantity of honey harvested	2	√	√	√	√	2, 9, 11, 12

Harvesting levels of different resource users (I1a)	Quantity of honey harvested by different beekeepers	3	√	√	√	√	2
Harvesting levels from different locations (I1b)	Quantity of honey harvested from different forage locations	3	√	√	√	√	14
Information sharing (I2)	Methods of information sharing among beekeepers	2	√	√	√	√	2, 9, 11, 12
Information sharing within formal resource user organization (I2a)	Information sharing within formal beekeeper groups	3		√	√	√	
Information sharing within informal resource user groups (I2b)	Information sharing among informal beekeeper groups	3		√	√	√	
Information sharing between resource user organization and government organizations (I2c)	Information sharing between government and industry organization	3		√	√	√	
Deliberation process (I3)	Presence of organizational structure for beekeepers' participation in decision making process	2	√	√	√	√	2, 9, 11, 12
Conflicts (I4)	Presence of existing conflicts among beekeepers and between beekeepers and other actors	2	√	√	√	√	2, 9, 11, 12
Conflicts among resource users (I4a)	Presence of conflicts among beekeepers	3		√		√	
Conflicts between resource users and other actors (I4b)	Presence of existing conflicts between beekeepers and other actors including government organizations	3		√	√	√	
Investment activities (I5)	Investment for improving and managing bee resources	2	√	√	√	√	2, 9, 11, 12
Investment in resource improvement and management (I5a)	Investment in resource improvement schemes	3		√	√	√	
Investment in industry relevant research and development activities (I5b)	Investment in research and development activities	3		√	√	√	
Lobbying activities (I6)	Presence of influential beekeepers	2	√	√	√	√	2, 9, 11, 12
Self-organizing activities (I7)	Internal rules made by beekeepers for resource extraction and management	2	√	√	√	√	2, 9, 11, 12

Networking activities (I8)	Networking and partnership activities among and outside beekeeper groups	2	√	√	√	√	2, 9, 11, 12
Monitoring activities (I9)	Monitoring activities on the use and management of resources	2	√	√	√	√	2, 9, 11, 12
Resource use monitoring activities (I9a)	Activities for monitoring bee resources	3		√		√	
Resource unit monitoring activities (I9b)	Beehive monitoring activities	3		√		√	
Evaluation Activities (I10)	Process of evaluation of resource condition and management initiatives	2	√	√	√	√	2, 9, 11, 12
Outcomes (O)	Beekeeping Outcomes (from key activities and processes)	1	√	√	√	√	9, 11
Socio-economic performance measure (O1)	Efficiency, equity and sustainability in apiary production	2	√	√	√	√	2, 9, 11, 12
Ecological performance (O2)	Biodiversity, resilience and sustainability of the bee resources	2	√	√	√	√	2, 9, 11, 12
Externalities to other SES (O3)	Non desired effects that occur as a result of processes	2	√	√	√	√	2, 9, 11, 12
Positive externalities (O3a)	Non desired positive effects that occur as a result of processes	3	√	√	√	√	2
Plant pollination (O3ai)	Unpaid plant pollination as a result of beehive migration process	4		√	√	√	
Packaged industries (O3aii) e.g. ecotourism,	Innovative industry model inspired from social-ecological benefits	4		√	√	√	
Negative externalities (O3b)	Non desired negative effects that occur as a result of processes	3	√	√	√	√	2
Resource competition with other species (O3bi)	Resource competition with other nectarivorous animals	4	√	√	√	√	4, 8
Disease transmission (O3bii)	Potential for disease transmission	4	√	√	√	√	3
Related ecosystems (ECO)	Other related ecosystems	1	√	√	√	√	9, 11
Climate pattern (ECO1)	Climate change or other biophysical change in the system	2	√	√	√	√	2, 9, 11, 12
Pollution pattern (ECO2)	Presence of toxic chemicals or materials	2	√	√	√	√	2, 9, 11, 12

Flows in and out of SES (ECO3)	Flows into and out of the focal SES	2	√		√	√	2, 9, 11, 12
Social, economic, and political settings (S)	Social, economic and political settings in which focal SES is located in	1	√	√	√	√	9, 11
Economic development (S1)	Economic growth of the area	2	√	√	√	√	2, 9, 11, 12
Demographic trend (S2)	Population growth and trends	2	√	√	√	√	2, 9, 11, 12
Political Stability (S3)	Regulatory framework of the region	2	√	√	√	√	2, 9, 11, 12
Other governance system (S4)	Traditional tenure or other government policies	2	√	√	√	√	2, 9, 11, 12
Markets (S5)	Environmental awareness and market demand	2	√	√	√	√	2, 9, 11, 12
Media organizations (S6)	Number, diversity and freedom of private and public media	2	√	√	√	√	2, 9, 11, 12
Technology (S7)	Presence of relevant technology	2	√	√	√	√	9, 11, 12

† Method column represent different methods used for stakeholder involvement: L – Literature research, I – Semi-structured interviews, O – Open ended discussion, W – Workshop with retired beekeepers.

‡ Numbers corresponds to the sources listed below.

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Appendix 2. Interview Themes

1. Interview Themes: Beekeepers

Migratory beekeeping

1. Number of hives in operation
2. Involvement in beekeeping
3. Hive management practices
4. Technology use
5. Factors considered for deciding forage location for hive migration
6. Factors affecting hive migration decisions
7. Governance in beekeeping systems

Market value of the apiary products

8. Decisions around price of products and factors influencing price
9. Cost associated with beekeeping
10. Aspirations of expanding business

Knowledge of Environmental Resources

11. Key target flora
12. A “good honey flow” and influencing factors
13. Predictability of spatial-temporal availability of a good flow

Identifying pressures on the industry

14. Factors influencing spatial-temporal availability of flowering events
15. Effects of beekeeping on the landscape
16. Any issues effecting the industry

Knowledge of the human-environment system

17. Understanding around key components from humans and the environment comprising the beekeeping system

2. Interview themes: Key informants

Questions for all organisations:

1. Levels of interaction with commercial beekeepers
2. Frequency of interaction with the WA bee industry
3. Role of the organization in WA bee industry
4. Key issues impacting the health and growth of the WA bee industry

Questions for permitting organisations:

5. Required permits for beekeeping in WA and process to obtain the permits
6. Rules governing the access to resources
7. Issues associated with resource access

Questions for land/resource management organisations:

8. Involvement with the industry
9. Current and previous resources management practices
10. Key issues associated with bee related land/resource management and the ways to deal with the issues

APPENDIX 3 - SESF VARIABLES FOR BEEKEEPING SES, THEIR DEFINITIONS AND METHODS USED TO IDENTIFY THEM.

Published as Appendix 1 in Patel, V., E. M. Biggs, N. Pauli, and B. Boruff. 2020. Using a social-ecological system approach to enhance understanding of structural interconnectivities within the beekeeping industry for sustainable decision-making. Ecology and Society 25(2):24.

Sources are listed if variable is found in published or unpublished literature. Note that both, SESF guiding literature and literature looking at bee systems explored to identify variables. In addition to literature, online sources such as government websites, rules and regulations had also supported variable identification process,

SESF variable for beekeeping industry (Focal SES)	Definition/Description	Tier	Method†				Sources ‡
			L	I	O	W	
Governance System (GS)	Bee governance system	1	√	√	√	√	9, 11
Government organization (GS1)	Government organizations managing and monitoring action situation for beekeeping industry system	2	√	√	√	√	2, 9, 11, 12
National level government organization (GS1a)	Federal government	3	√	√	√	√	2
State level government organizations (GS1b)	State government	3	√	√	√	√	2
Local Government (GS1c)	Local government	3		√		√	
Non-government org (GS2)	Presence of non- government organization managing and monitoring action situation for beekeeping industry system	2	√	√	√	√	2, 9, 11, 12
Industry organizations (GS2a)	Industry owned and operated organizations that collectively represent various beekeepers associations (e.g. BICWA)	3		√	√	√	
Beekeepers associations (GS2ai)	Presence of various beekeepers associations such as commercial, semi-commercial and hobby beekeepers associations	4		√		√	
Queen breeders (GS2aii)	Queen bee breeders group that rears and provides queen bees to the state due to closed borders	4		√	√	√	
Industry leaders (GS2aiii)	Leading WA beekeepers who are positioned at industry organizations, involved in lobbying activities, brings investment for the development of the industry, provide	4				√	

	knowledge about resources and beekeeping techniques to new beekeepers						
Research organizations (GS2b)	Organizations actively engaged in research related to various aspects of the beekeeping industry	3	√	√	√	√	17
University research (GS2bi)	Student and researchers from universities involved in the research beneficial to the beekeeping industry	4		√		√	
Industry funded research (GS2bii)	Research funded by industry owned and operated organizations (targets industry specific issues, beekeeper researchers)	4		√		√	
Cooperative Research centres (CRCs)	Collaborative research involvement from government, non-government organizations (e.g. CRC for honeybee products)	4		√	√	√	
Network Structure (GS3)	Social or political connections among government / no-government organizations, beekeepers and other industry stakeholders.	2	√	√	√	√	2, 9, 11, 12
Social network (GS3a)	Social connections between beekeepers and government or private land owners/managers	3	√	√	√	√	2
Informal beekeeper groups (GS3ai)	Information flows among groups of beekeepers (e.g. information regarding resource availability and access)	4		√		√	
Market network (GS3b)	Presence or absences of multilevel of market structure and associated interactions	3		√			
Local farmers' market (GS3bi)	Regular or occasional local markets and fresh food produce outlets	4		√		√	
Supermarkets (GS3bii)	Supermarket networks	4		√		√	
Export market (GS3biii)	Export market and associated interactions	4		√	√	√	
Property rights systems (GS4)	Presence of property rights system governing access to forage resources (e.g. private property, common property, restricted access)	2	√	√	√	√	2, 9, 11, 12
Operational choice rules (GS5)	Presence of formal written rules for access and/or harvesting from the forage resources	2	√	√	√	√	2, 9, 11, 12
Collective choice rules (GS6)	Rules defined by involved stakeholders following their understanding of local social, ecological and political conditions	2	√		√	√	2, 9, 11, 12
Constitutional choice rules (GS7)	Law, act or mandates defined by regional or national level government	2	√	√	√	√	2, 9, 11, 12
Act relating to beekeeping activity (GS7a)	Biosecurity and Agriculture Management Act 2007	3		√	√	√	19

Act relating to biosecurity (GS7b)	Biosecurity and Agriculture Management Regulation 2013	3		√	√	√	19
Acts relating to access and use of resources (GS7c)	Conservation and land management Act 1984, , Biodiversity Conservation Act 2016 and Biodiversity Conservation Regulations 2018	3	√	√	√	√	22
Conditions for using resources available on Government owned land (GS7ci)	General Conditions for using Apiary Authorities on Crown land in Western Australia	4	√	√	√	√	24
Forest management plans (GS7cii)	Planning for management of forest used for apiary authority	4		√	√	√	20
Local government Acts or Bylaws (GS7ciii)	Verge treatment/spraying , regulations relating to keeping bees in neighbourhood	4		√		√	
Conditions for using resources managed by managers other than government (GS7civ)	Recreation, mining, timber and logging, pastoral leases	4	√	√	√	√	23
Requirements relating to food handling, processing and labelling (GS7d)	Regulation for extraction, processing, packing and labelling of honey	3		√		√	21
Monitoring and sanctioning rules (GS8)	Presence of authority to for resource monitoring and access sanctioning	2	√	√	√	√	2, 9, 11, 12
Sanctioning rules (GS8a)	Process of sanctioning authority to access the resources	3	√	√	√	√	2
Apiary permits (GS8ai)	Authority to place beehives on forage locations	4	√	√	√	√	16, 26
Clearing permits (GS8aii)	Authority to clear vegetation to gain physical access and place beehives on forage locations	4	√	√	√	√	24
Monitoring rules (GS8b)	Process of monitoring resource availability and usage	3	√	√		√	2
Apiary site monitoring (GS8bi)	Monitoring resource use on apiary authority	4		√		√	
Monitoring beehives (GS8bii)	Monitoring requirement and availability of required resources	4		√		√	
Actors (A)	Beekeepers	1	√	√	√	√	7, 9, 11

Number of actors (A1)	Number of beekeepers	2	√	√	√	√	9, 12
Socio-economic attributes (A2)	Socio-economic characteristics of beekeepers	2	√	√	√	√	2, 9, 11, 12
Demographic attributes (A2a)	Age of beekeepers	3	√	√	√	√	2, 13
Intergenerational beekeeper (A2ai)	Beekeeping generation	4		√	√	√	
Economic attributes (A2b)	Economic characteristic of beekeeper	3	√	√	√	√	2
Large-scale operators (A2bi)	Beekeepers more than 500 hives	4		√	√	√	
Small-scale operators (A2bii)	Beekeeper less than 500 hives	4		√	√	√	
Equipment manufacturer/supplier (A2biii)	Manufacturer / supplier of beekeeping equipment (May or may not be keeping bees)	4		√		√	
Producer, packers and queen bee breeders (A2biv)	Beekeepers involved in honey packing or queen breeding	4		√	√	√	
Social attributes (A2c)	Presence of mutual support, cooperation and leadership quality	3	√	√	√	√	2
History of past experience (A3)	Duration of involvement in beekeeping	2	√	√	√	√	2, 9, 11, 12
Location (A4)	Residential location of beekeepers	2	√	√	√	√	2, 9, 11, 12
Leadership/ Entrepreneurship (A5)	Presence of educated and well-connected leader who is respected by their peers	2	√	√	√	√	2, 9, 11, 12
Volunteer leaders (A5a)	Active beekeeper to lead collective action	3		√	√	√	
Training for beekeeping business (A5b)	Beekeeper involved in providing formal/informal training for new beekeepers	3		√		√	
Norms and social capital (A6)	Closeness of community	2	√	√	√	√	2, 9, 11, 12
Social interaction (A6a)	Interactions and knowledge exchange among beekeepers	3		√		√	
Trust among actors (A6b)	Level of trust among beekeepers	3		√	√	√	
Relationship with other actors (A6c)	Relationship of beekeepers with actors other than the focal SES (e.g. farmers, local residents, consumers)	3		√		√	

Knowledge of SES models (A7)	Presence/ degree of Local ecological knowledge (LEK)	2	√	√	√	√	2, 9, 11, 12
Local knowledge on SES (A7a)	Spatial- temporal knowledge of floral source and understanding of effects of beekeeping activities on local environment	3	√	√	√	√	2, 12
Knowledge of concepts such as conservation, human-nature relationships (A7d)	Presence / degree of understanding of concepts like conservation, ecosystem services and human-nature relationship	3	√	√	√	√	2, 12
Knowledge of the biological shocks on SES (A7b)	Level of knowledge of the potential and real disturbance patterns and its possible effects	3	√	√	√	√	2, 12
Importance of resource (dependence) (A8)	Livelihood dependence on bee resources	2	√	√	√	√	2, 9, 11, 12
Full-time operators (A8a)	Completely depend on beekeeping for livelihood	3		√	√	√	
Part-time operators (A8b)	Has a source of income other than beekeeping	3		√	√	√	
Technologies available (A9)	Technologies used to identify, extract, harvest and manage the resource (A9)	2	√	√	√	√	2, 9, 11, 12
Resource system (RS)	Bee resources - Resources that produce melliferous flora	1	√	√	√	√	7, 9, 11
Sector (RS1)	Bee resources available on various sector (e.g. forest)	2	√	√	√	√	2, 9, 11, 12
Forest flora (RS1a)	Bee resources available from trees and other understorey plants in forest	3	√	√	√	√	7
Agriculture flora (RS1b)	Bee resources available from agriculture crops	3	√	√	√	√	7
Other plantation (RS1c)	Bee resources available from plantation	3	√	√	√	√	7
Revegetation (RS1ci)	Bee resources available from revegetation	4	√	√	√	√	7
Verge plantation (RS1cii)	Bee resources available from plantation on new or existing verge	4	√	√		√	6
Clarity of system boundary (RS2)	Clarity of the system's geographical, social and legal boundaries	2	√	√	√	√	2, 9, 11, 12
Geographic boundaries (RS2a)	Geographic boundary of bee resources	3	√				2
Anthropogenic boundaries (RS2b)	Fences or other human constructed boundaries	3	√	√	√	√	2

Individual's resource access boundary (RS2c)	User-defined boundary for the bee resources	3	√	√	√	√	2, 18
Size of the resource system (RS3)	Spatial extent and its area of bee resources	2	√	√	√	√	2, 9, 11, 12
Area covered by geographic extent of bee resources (RS3a)	Total area for bee resources	3	√	√	√	√	18
Size of different types of ecosystems within the extent of bee resources (RS3b)	Total area for each sector of bee resources	3	√		√		18
Fragmentation dynamics (RS3c)	Frequency of fragmentation over time	3	√		√		18
Human constructed facilities (RS4)	Anthropogenic structures supporting resource access and management	2	√	√	√	√	2, 9, 11, 12
Infrastructure e.g. road, highways (RS4a)	Availability of infrastructure for movement (e.g. roads, access ways) or as impediments (e.g. dams, fence)	3	√	√	√	√	2, 18
Water resources (RS4b)	Proximity to the nearest water resources	3		√		√	
Other facilities (RS4c)	Recreation facilities	3		√		√	
Productivity of the system (RS5)	Estimation about potential productivity of the area	2	√	√	√	√	2, 9, 11, 12
Resource dynamics (RS5a)	Regularity of flowering events	3	√	√	√	√	18
Natural resource dynamics (RS5ai)	Natural availability or unavailability of flowering event e.g. annual, biannual flowering frequency	4		√	√	√	
Resource dynamics in response to human disturbances (RS5aii)	Availability or unavailability of flowering due to man-made changes e.g. flowering event after species recovery from prescribed fire	4		√	√	√	
Resource diversity (RS5b)	Diversity of bee flora species	3	√	√	√	√	1
Equilibrium properties of the system (RS6)	Positive or negative influences on the equilibrium of the bee resources (e.g. seasonality, rainfall trends)	2	√	√	√	√	2, 9, 11, 12
Frequency of disturbances (RS6a)	Frequency of external impacts and system response e.g. frequency of draught/fire events and species recovery	3	√	√	√	√	18
Extent of disturbances (RS6b)	Extent of external impacts and system response e.g. extent of draught/fire events and species recovery	3	√	√	√	√	18

Intensity of disturbances (RS6c)	Intensity of external impacts and system response e.g. Intensity of draught/fire events and species recovery	3	√	√	√	√	18
Predictability of system dynamics (RS7)	Degree to which beekeepers are able to forecast/identify patterns in productivity of bee resources	2	√	√	√	√	2, 9, 11, 12
Probability of driving forces leading to system dynamics (RS7a)	Probability of driving forces e.g. uncertain nature of rainfall or natural fire events	3	√	√	√	√	18
Variability of driving forces leading to system dynamics (RS7b)	Variability of driving force e.g. variation in nectar production	3	√	√	√	√	18
Storage characteristics (RS8)	Information storage regarding effects of disturbances on bee resources	2	√	√	√	√	2, 9, 11, 12
Location and association (RS9)	Spatial configuration and extent of bee flora where system can be accessed by the beekeepers	2	√	√	√	√	2, 9, 11, 12, 18
Ecosystem history (RS10)	History of ecosystem dynamics	2	√	√	√	√	18
History of natural disasters (RS10a)	History of draught or bush fire events	3	√	√	√	√	18
History of anthropogenic use and disturbances (RS10b)	History of prescribe burn events	3	√	√	√	√	18
Resource unit (RU)	Beehives managed by beekeepers	1	√	√	√	√	5, 9, 11
Mobility of Resource units (RU1)	Beehive migration patterns	2	√	√	√	√	2, 9, 11, 12
Stationary Resource units (RU1a)	Stationary (non-migratory) beehives	3	√	√		√	18
Mobile Resource units (RU1b)	Migration patterns of beehives	3	√	√	√	√	9, 11, 18
Growth or replacement rate (RU2)	Absolute or relative descriptions of changes in quantities (x) of beehives over time (t)	2	√	√	√	√	2, 9, 11, 12
Interactions among resource units (RU3)	Interactions among beehives managed by same or different beekeeper	2	√	√	√	√	2, 9, 11, 12
Intraspecific interaction (RU3a)	Resource competition within honeybee species e.g. Hive robbing	3	√	√	√	√	18

Proximity of resource units (RU3ai)	Inter/intra colony distance among beehives	4	√	√		√	10, 24
Interactions damaging resource unit conditions (RU3aii)	Potential for disease transmission	4	√	√		√	10
Interspecific resource competition (RU3b)	Resource competition among nectarivorous species e.g. for nesting or forage resources	3	√	√	√	√	18
Value of resource unit (RU4)	Value of a beehive	2	√	√	√	√	2, 9, 11, 12
Market value (RU4a)	Cost associated with a beehive (e.g. levy, insurance etc.)	3	√	√	√	√	2
Environmental value (RU4b)	Non-monatory value of a beehive (e.g. importance for pollination)	3	√	√	√	√	2
Strategic value (RU4c)	Social/cultural value of a beehive (e.g. importance as a hobby)	3	√	√	√	√	2
Number of units (RU5)	Number of managed hives	2	√	√	√	√	2, 9, 11, 12
Number of units leading to economic benefit (RU5a)	Hives managed for economic benefits	3		√		√	
Load size (RU5ai)	Number of hives managed for honey production	4		√		√	
Number of units leading to economic and environmental benefits (RU5b)	Hives managed for pollination services	3		√		√	
Distinctive characteristics (RU6)	Colouring / numbering of hives aiming identifying individual loads	2	√	√	√	√	2, 9, 11, 12
Distinctive markings (RU6a)	Marking beehives with brand code	3	√	√		√	
Spatial and Temporal distribution (RU7)	Beehive migration patterns	2	√	√	√	√	2, 9, 11, 12
Spatial patchiness (RU7a)	Hive migration on fragmented landscape	3	√	√		√	18
Temporal patchiness (RU7b)	Hive migration following phenology and patchy flowering	3	√	√		√	18
Interactions (I)	Key activities and processes in beekeeping	1	√	√	√	√	9, 11
Harvesting (I1)	Quantity of honey harvested	2	√	√	√	√	2, 9, 11, 12

Harvesting levels of different resource users (I1a)	Quantity of honey harvested by different beekeepers	3	√	√	√	√	2
Harvesting levels from different locations (I1a)	Quantity of honey harvested from different forage locations	3	√	√	√	√	14
Information sharing (I2)	Methods of information sharing among beekeepers	2	√	√	√	√	2, 9, 11, 12
Information sharing within formal resource user organization (I2a)	Information sharing within formal beekeeper groups	3		√	√	√	
Information sharing within informal resource user groups (I2b)	Information sharing among informal beekeeper groups	3		√	√	√	
Information sharing between resource user organization and government organizations (I2c)	Information sharing between government and industry organization	3		√	√	√	
Deliberation process (I3)	Presence of organizational structure for beekeepers' participation in decision making process	2	√	√	√	√	2, 9, 11, 12
Conflicts (I4)	Presence of existing conflicts among beekeepers and between beekeepers and other actors	2	√	√	√	√	2, 9, 11, 12
Conflicts among resource users (I4a)	Presence of conflicts among beekeepers	3		√		√	
Conflicts between resource users and other actors (I4b)	Presence of existing conflicts between beekeepers and other actors including government organizations	3		√	√	√	
Investment activities (I5)	Investment for improving and managing bee resources	2	√	√	√	√	2, 9, 11, 12
Investment in resource improvement and management (I5a)	Investment in resource improvement schemes	3		√	√	√	
Investment in industry relevant research and development activities (I5b)	Investment in research and development activities	3		√	√	√	
Lobbying activities (I6)	Presence of influential beekeepers	2	√	√	√	√	2, 9, 11, 12
Self-organizing activities (I7)	Internal rules made by beekeepers for resource extraction and management	2	√	√	√	√	2, 9, 11, 12

Networking activities (I8)	Networking and partnership activities among and outside beekeeper groups	2	√	√	√	√	2, 9, 11, 12
Monitoring activities (I9)	Monitoring activities on the use and management of resources	2	√	√	√	√	2, 9, 11, 12
Resource use monitoring activities (I9a)	Activities for monitoring bee resources	3		√		√	
Resource unit monitoring activities (I9b)	Beehive monitoring activities	3		√		√	
Evaluation Activities (I10)	Process of evaluation of resource condition and management initiatives	2	√	√	√	√	2, 9, 11, 12
Outcomes (O)	Beekeeping Outcomes (from key activities and processes)	1	√	√	√	√	9, 11
Socio-economic performance measure (O1)	Efficiency, equity and sustainability in apiary production	2	√	√	√	√	2, 9, 11, 12
Ecological performance (O2)	Biodiversity, resilience and sustainability of the bee resources	2	√	√	√	√	2, 9, 11, 12
Externalities to other SES (O3)	Non desired effects that occur as a result of processes	2	√	√	√	√	2, 9, 11, 12
Positive externalities (O3a)	Non desired positive effects that occur as a result of processes	3	√	√	√	√	2
Plant pollination (O3ai)	Unpaid plant pollination as a result of beehive migration process	4		√	√	√	
Packaged industries (O3aii) e.g. ecotourism,	Innovative industry model inspired from social-ecological benefits	4		√	√	√	
Negative externalities (O3b)	Non desired negative effects that occur as a result of processes	3	√	√	√	√	2
Resource competition with other species (O3bi)	Resource competition with other nectarivorous animals	4	√	√	√	√	4, 8
Disease transmission (O3bii)	Potential for disease transmission	4	√	√	√	√	3
Related ecosystems (ECO)	Other related ecosystems	1	√	√	√	√	9, 11
Climate pattern (ECO1)	Climate change or other biophysical change in the system	2	√	√	√	√	2, 9, 11, 12
Pollution pattern (ECO2)	Presence of toxic chemicals or materials	2	√	√	√	√	2, 9, 11, 12

Flows in and out of SES (ECO3)	Flows into and out of the focal SES	2	√		√	√	2, 9, 11, 12
Social, economic, and political settings (S)	Social, economic and political settings in which focal SES is located in	1	√	√	√	√	9, 11
Economic development (S1)	Economic growth of the area	2	√	√	√	√	2, 9, 11, 12
Demographic trend (S2)	Population growth and trends	2	√	√	√	√	2, 9, 11, 12
Political Stability (S3)	Regulatory framework of the region	2	√	√	√	√	2, 9, 11, 12
Other governance system (S4)	Traditional tenure or other government policies	2	√	√	√	√	2, 9, 11, 12
Markets (S5)	Environmental awareness and market demand	2	√	√	√	√	2, 9, 11, 12
Media organizations (S6)	Number, diversity and freedom of private and public media	2	√	√	√	√	2, 9, 11, 12
Technology (S7)	Presence of relevant technology	2	√	√	√	√	9, 11, 12

† Method column represent different methods used for stakeholder involvement: L – Literature research, I – Semi-structured interviews, O – Open ended discussion, W – Workshop with retired beekeepers.

‡ Numbers corresponds to the sources listed below.

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APPENDIX 4 - INTERVIEW THEMES

Published as Appendix 2 in : Patel, V., E. M. Biggs, N. Pauli, and B. Boruff. 2020. Using a social-ecological system approach to enhance understanding of structural interconnectivities within the beekeeping industry for sustainable decision-making. Ecology and Society 25(2):24.

1. Interview Themes: Beekeepers

Migratory beekeeping

1. Number of hives in operation
2. Involvement in beekeeping
3. Hive management practices
4. Technology use
5. Factors considered for deciding forage location for hive migration
6. Factors affecting hive migration decisions
7. Governance in beekeeping systems

Market value of the apiary products

8. Decisions around price of products and factors influencing price
9. Cost associated with beekeeping
10. Aspirations of expanding business

Knowledge of Environmental Resources

11. Key target flora
12. A "good honey flow" and influencing factors
13. Predictability of spatial-temporal availability of a good flow

Identifying pressures on the industry

14. Factors influencing spatial-temporal availability of flowering events
15. Effects of beekeeping on the landscape
16. Any issues effecting the industry

Knowledge of the human-environment system

17. Understanding around key components from humans and the environment comprising the beekeeping system

2. Interview themes: Key informants

Questions for all organisations:

1. Levels of interaction with commercial beekeepers
2. Frequency of interaction with the WA bee industry
3. Role of the organization in WA bee industry
4. Key issues impacting the health and growth of the WA bee industry

Questions for permitting organisations:

5. Required permits for beekeeping in WA and process to obtain the permits
6. Rules governing the access to resources
7. Issues associated with resource access

Questions for land/resource management organisations:

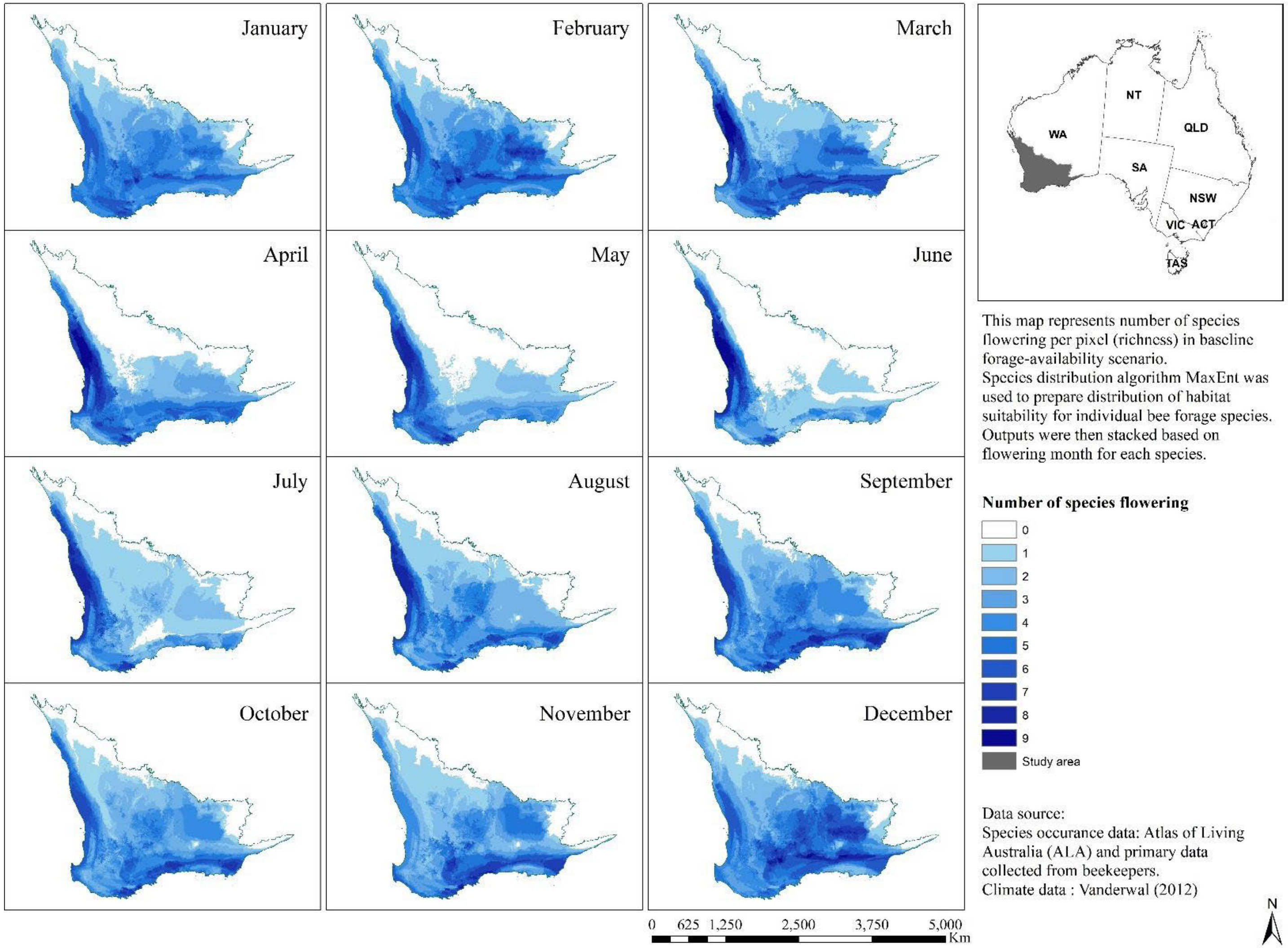
8. Involvement with the industry
9. Current and previous resources management practices
10. Key issues associated with bee related land/resource management and the ways to deal with the issues

APPENDIX 5 - BEE FORAGE SPECIES DISTRIBUTIONS IN WESTERN AUSTRALIA

Appendix B in the submission in revision with Applied Geography - Patel, V., E. M. Biggs, N. Pauli, and B. Boruff. 2022. *B-Agent*: A hybrid modelling approach for assessing the influence of variation in forage availability on spatial patterns of beehive migration.

Table 5.1: Six Bioclimate variables used in the species distribution model.

Code	Variable
BIO3	Isothermality
BIO5	Max temperature of warmest month
BIO11	Mean temperature of coldest quarter
BIO12	Annual precipitation
BIO16	Precipitation of wettest quarter
BIO17	Precipitation of driest quarter



January
February
March
April
May
June
July
August
September
October
November
December
NT
WA
QLD
SA
NSW
VIC ACT
TAS
This map represents number of species flowering per pixel (richness) in baseline forage-availability scenario.
Species distribution algorithm MaxEnt was used to prepare distribution of habitat suitability for individual bee forage species. Outputs were then stacked based on flowering month for each species.
Number of species flowering
0
1
2
3
4
5
6
7
8
9
Study area
Data source:
Species occurance data: Atlas of Living Australia (ALA) and primary data collected from beekeepers.
Climate data : Vanderwal (2012)
0 625 1,250 2,500 3,750 5,000
Km
N

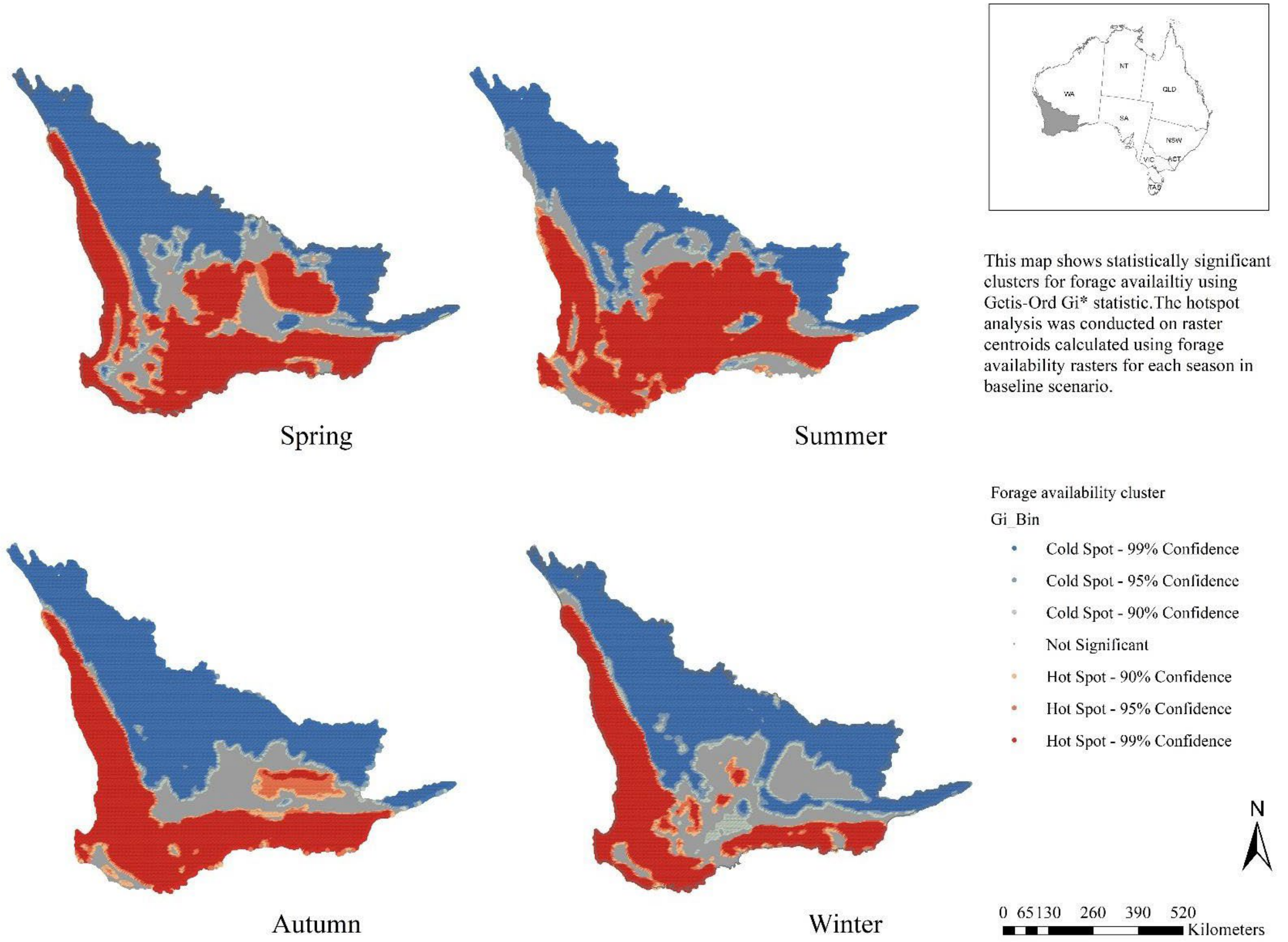


Figure 5.2: Statistically significant spatial clusters of high richness of bee forage species in Southwest Western Australia in baseline scenario. Red colours represent greater numbers of species flowering within the pixel (high species richness).

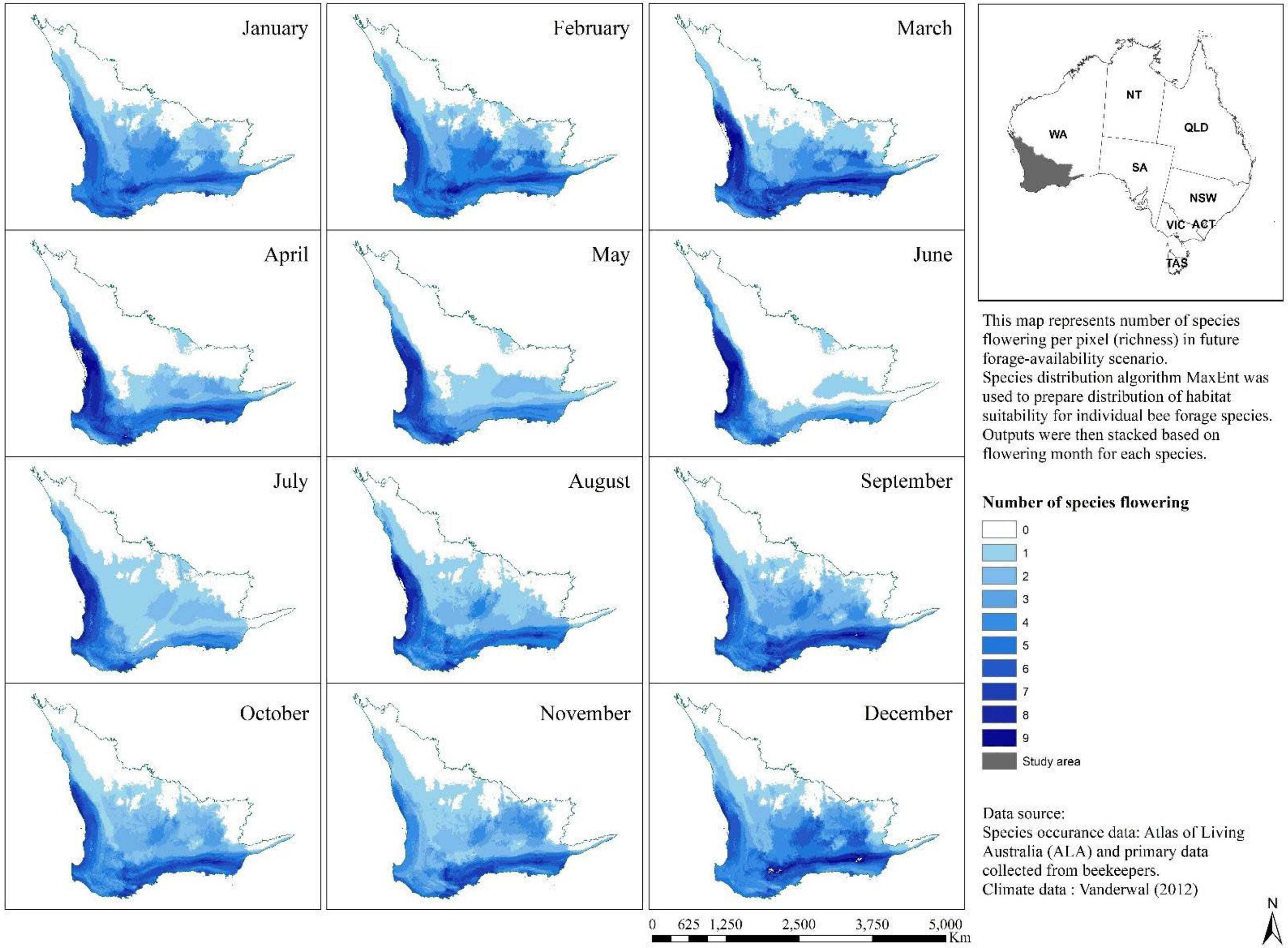


Figure 5.3: Spatial distribution of forage availability (richness of bee forage species) in Southwest Western Australia in future scenario. Dark blue colours represent greater numbers of species flowering within a pixel (high species richness).

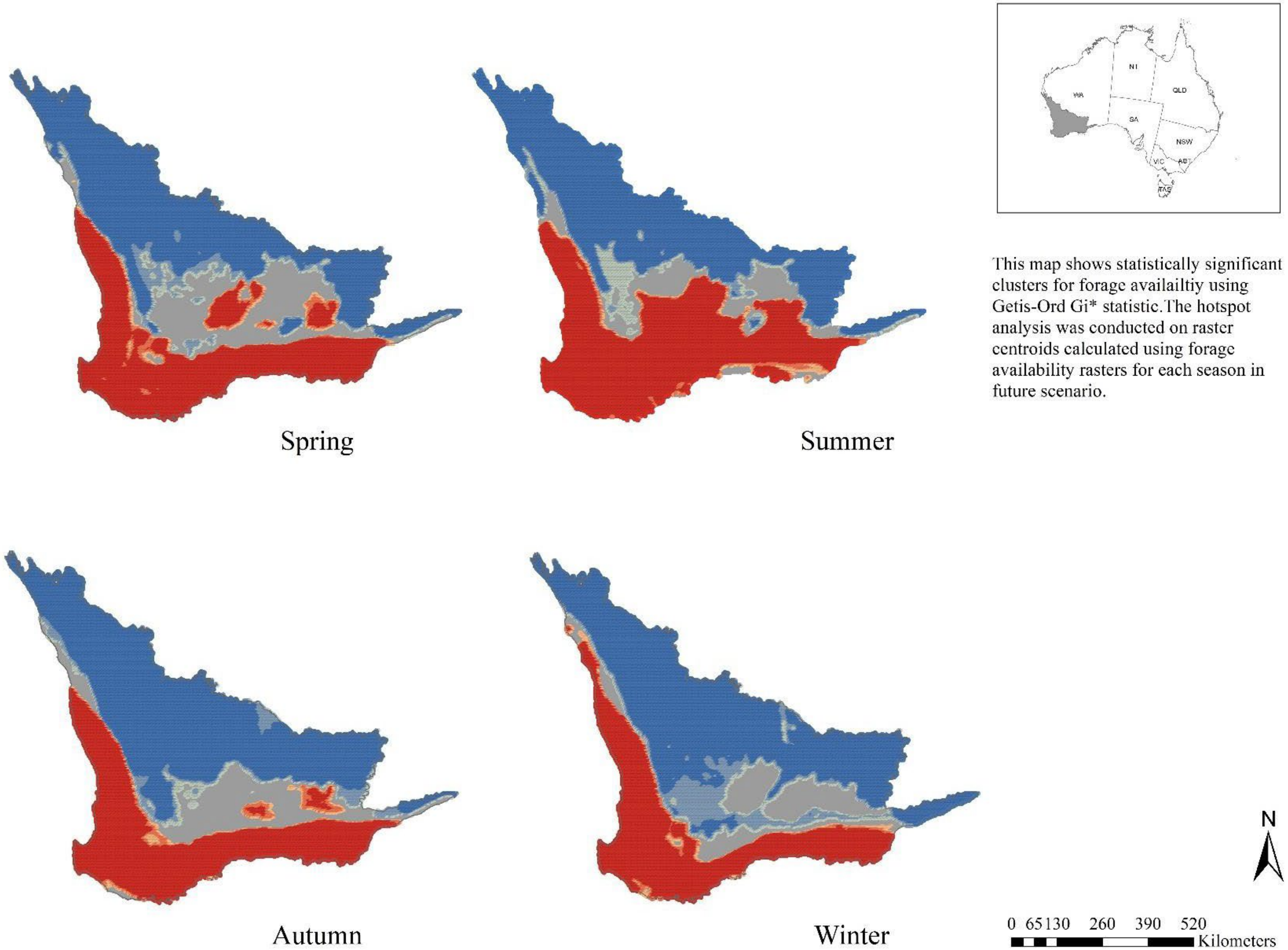


Figure 5.4: Statistically significant spatial clusters of high richness of bee forage species in Southwest Western Australia in future scenario. Red colours represent greater numbers of species flowering within a pixel (high species richness).

Table 5.3: Mean statistics representing change in premium forage availability between baseline and future scenarios aggregated to biogeographic subregions in WA using Zonal statistics in QGIS. Negative values suggest an increase in the availability whereas positive values corresponds to the loss of availability of premium species.

Biogeographic regions	**Biogeographic subregions**	**Mean pixel value for Marri**	**Mean pixel value for Jarrah**
Esperance Plains	Fitzgerald	0.00	0.1
Esperance Plains	Recheche	-0.1	0.0
Geraldton Sandplains	Lesueur Sandplain	0.2	0.1
Jarrah Forest	Northern Jarrah Forest	0.1	0.2
Jarrah Forest	Southern Jarrah Forest	0.1	0.1
Swan Coastal Plain	Dandaragan Plateau	0.4	0.4
Swan Coastal Plain	Perth	0.1	0.5

Table 5.4: Evaluation statistics (AUC and TSS) for individual species distribution models in moderate emission (RCP 6.0) and high emission (RCP8.5) future climate scenario. Here, AUC values represent mean values derived from fivefold MaxEnt modelling.

Target species	**Training AUC**	**RCP 6.0**		**RCP 8.5**	
		Test AUC	**TSS**	**Test AUC**	**TSS**
Banksia attenuata	0.96	0.95	0.79	0.95	0.79
Banksia menziesii	0.99	0.99	0.91	0.98	0.91
Banksia sessilis	0.95	0.93	0.78	0.94	0.78
Banksia sphaerocarpa	0.94	0.90	0.68	0.89	0.68
Calothamnus quadrifidus	0.88	0.87	0.67	0.84	0.67
Corymbia calophylla	0.93	0.93	0.82	0.92	0.82
Eucalyptus accedens	0.97	0.97	0.87	0.96	0.85
Eucalyptus annulata	0.96	0.94	0.76	0.94	0.77
Eucalyptus burracoppinensis	0.96	0.92	0.77	0.93	0.76
Eucalyptus cornuta	0.98	0.98	0.87	0.97	0.86
Eucalyptus diversicolor	0.99	0.99	0.92	0.98	0.92
Eucalyptus dundasii	0.99	0.98	0.88	0.98	0.90
Eucalyptus flocktoniae	0.87	0.90	0.67	0.84	0.64
Eucalyptus incrassata	0.91	0.87	0.70	0.87	0.71
Eucalyptus lesouefii	0.98	0.98	0.84	0.97	0.85
Eucalyptus longicornis	0.86	0.88	0.69	0.83	0.69
Eucalyptus loxophleba	0.80	0.78	0.64	0.77	0.63
Eucalyptus marginata	0.94	0.93	0.83	0.93	0.84
Eucalyptus melanoxylon	0.92	0.90	0.67	0.88	0.66
Eucalyptus occidentalis	0.94	0.91	0.74	0.92	0.74
Eucalyptus platypus	0.97	0.94	0.78	0.93	0.77
Eucalyptus ravida	0.95	0.96	0.77	0.93	0.76
Eucalyptus redunca	0.96	0.93	0.67	0.93	0.69
Eucalyptus salubris	0.87	0.86	0.55	0.83	0.54
Eucalyptus stricklandii	0.99	0.98	0.81	0.97	0.84
Eucalyptus transcontinentalis	0.93	0.90	0.68	0.89	0.67
Eucalyptus wandoo	0.93	0.93	0.74	0.92	0.75
Hakea trifurcata	0.93	0.91	0.70	0.91	0.71
Leucopogon conostephioides	0.93	0.93	0.67	0.90	0.67
Leucopogon oldfieldii	0.99	0.99	0.93	0.98	0.94

Table 5.5: Shift in magnitude and direction of species spatial distribution ranges from baseline to future (including moderate and high emission scenarios. The shift direction was calculated as 45-degree intervals to represent North (348.75 - 33.75); Northeast (33.75 -78.75); East (78.75-123.75); Southeast (123.75 – 168.75); South (168.75 - 213.75); Southwest (213.75 - 258.75); West (258.75 - 303.75), and Northwest (303.75 - 348.75).

Target species	**RCP 6.0**			**RCP 8.5**		
	Change [%]	**Shift [km]**	**Direction**	**Change [%]**	**Shift [km]**	**Direction**
Banksia attenuata	-0.5	133.8	SE	1.2	170.5	SE
Banksia menziesii	-2.1	124.4	S	6	179.4	S
Banksia sessilis	-16.7	65.5	S	-16.5	117.8	S
Banksia sphaerocarpa	-9.5	41.6	SE	-18.9	58.8	S
Calothamnus quadrifidus	8.2	135.6	SE	44.9	194.3	SE
Corymbia calophylla	-21.5	34.2	S	-30.5	52.2	S
Eucalyptus accedens	1.0	44.7	S	-7.4	73.5	S
Eucalyptus annulata	-63.6	110.3	SW	-81.4	78.7	SW
Eucalyptus burracoppinensis	-46.9	71.8	S	-43.9	87.0	E
Eucalyptus cornuta	-41.0	42.1	SW	-48.5	88.1	SW
Eucalyptus diversicolor	-40.4	16.0	S	-40.3	12.9	S
Eucalyptus dundasii	0.7	4.9	SW	-77.5	56.4	W
Eucalyptus flocktoniae	-47.7	62.3	SE	-50.2	90.8	SE
Eucalyptus incrassata	-6.1	10.9	E	6.9	39.4	E
Eucalyptus lesouefii	-59.0	30.0	E	-85.2	17.7	S
Eucalyptus longicornis	-13.4	69.0	S	18.7	66.4	SE
Eucalyptus loxophleba	-4.3	63.2	S	-2.5	105.9	SE
Eucalyptus marginata	-26.9	37.8	S	-38.6	52.3	S
Eucalyptus melanoxylon	14.2	44.8	SW	22.9	66.2	SW
Eucalyptus occidentalis	-18.8	25.9	E	-19.6	68.1	E
Eucalyptus platypus	-24.2	18.5	S	-24.8	20.4	SE
Eucalyptus ravida	-21.9	44.6	S	-55.6	75.5	S
Eucalyptus redunca	-47.8	101.5	E	-12.5	27.5	SE
Eucalyptus salubris	-25.8	97.1	S	-4.4	91.9	SE
Eucalyptus stricklandii	-16.1	28.0	SE	-49.2	29.2	E
Eucalyptus transcontinentalis	-13.1	55.1	SE	-1.9	48.1	S
Eucalyptus wandoo	-28.3	60.5	S	-31.2	101.0	S
Hakea trifurcata	-4.8	69.7	SE	-2.9	121.1	SE
Leucopogon conostephioides	35.9	119.2	SE	57.6	152.2	SE
Leucopogon oldfieldii	12.2	80.1	SE	9.7	125.0	S

Table 5.6: Annual distance travelled by commercial and semi-commercial beekeepers in baseline, moderate emission (RCP6.0), and high emission (RCP8.5) future scenarios.

Beekeeper class	Baseline travel (km)	Future (RCP6.0) travel (km)	Future (RCP8.5) travel (km)
Commercial	16169.2	16492.7	16008.1
Semi-commercial	1076.2	1060.7	1036.5

Table 5.7: Patterns in the frequency of beehive migration in baseline, moderate emission (RCP6.0), and high emission (RCP8.5) future scenarios.

Month	Baseline		Future (RCP6.0)		Future (RCP8.5)	
	Mean shifting beekeepers	Mean Beekeepers with no target found	Mean shifting beekeepers	Mean Beekeepers with no target found	Mean shifting beekeepers	Mean Beekeepers with no target found
August	0.83	1.04	0.83	1.68	0.84	2.00
September	0.84	1.04	0.85	1.68	0.86	2.00
October	0.85	1.04	0.87	1.68	0.88	2.00
November	0.86	1.04	0.88	1.68	0.9	2.00
December	0.88	1.04	0.9	1.68	0.92	2.00
January	0.89	1.04	0.92	1.96	0.94	2.00
February	0.9	1.04	0.94	1.96	0.96	2.00
March	0.92	1.04	0.96	1.96	0.98	2.00
April	0.93	1.04	0.99	1.96	1.02	2.38
May	0.96	1.08	1.01	1.96	1.04	2.38
June	0.97	1.08	1.03	1.96	1.08	2.88
July	0.99	1.08	1.05	1.96	1.1	2.88

Table 5.8: Shift in forage locations harvested by beekeepers from baseline to moderate and high emission future scenarios. The shift is calculated using raster outputs of harvested forage cells from 100 runs of hive migration ABM with forage availability inputs prepared for each climate scenario.

Forage availability Scenarios	**The shift in forage location harvested by beekeepers**		
	Distance (km)	**Direction (degrees)**	**Direction**
Moderate emission (RCP6.0)	126.43	107	E
High emission (RCP8.5)	77.18	91	E

APPENDIX 6 - THE HIVE MIGRATION ABM NetLogo CODE

Appendix C in the submission in review with Applied Geography - Patel, V., E. M. Biggs, N. Pauli, and B. Boruff. 2023. Assessing the influence of variation in forage availability on spatial patterns of beehive migration using a hybrid modelling approach - B-Agent

```
;                                                                                                    n

extensions [ gis csv]


globals [
  res_town                  ;;; Vector-data for beekeepers' residential postcodes
  res_patches               ;;; NetLogo patches that intersect res_town boundary
  study_area                ;;; Vector-data for study area
  model_patches             ;;; NetLogo patches that intersect study area boundary
  forage_model_patches      ;;; Patches intersecting study_area that has flowering available_forage during any month of the year
  num_months                ;;; Variable resenting number of months used to create monthly timestep
  jan_availability          ;;; Raster_data for distribution of bee forage species that flowers in January
  feb_availability          ;;; Raster_data for distribution of bee forage species that flowers in February
  mar_availability          ;;; Raster_data for distribution of bee forage species that flowers in March
  apr_availability          ;;; Raster_data for distribution of bee forage species that flowers in April
  may_availability          ;;; Raster_data for distribution of bee forage species that flowers in May
  jun_availability          ;;; Raster_data for distribution of bee forage species that flowers in June
  jul_availability          ;;; Raster_data for distribution of bee forage species that flowers in July
  aug_availability          ;;; Raster_data for distribution of bee forage species that flowers in August
  sep_availability          ;;; Raster_data for distribution of bee forage species that flowers in September
  oct_availability          ;;; Raster_data for distribution of bee forage species that flowers in October
  nov_availability          ;;; Raster_data for distribution of bee forage species that flowers in November
  dec_availability          ;;; Raster_data for distribution of bee forage species that flowers in December
  JanP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in January
  FebP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in February
  MarP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in March
  AprP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in April
  MayP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in May
  JunP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in June
  JulP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in July
  AugP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in August
  SepP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in September
  OctP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in October
  NovP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in November
  DecP_data                 ;;; Raster_data for distribution of premium bee forage species that flowers in December
  ;proximity                ;;; Maximum distance that beekeepers are willing to travel from their home location - set to 300.
                            ;;; The values can be changed from the interface according to user's preference
  ;spread                   ;;; Preference for maximum distance between individual loads - set to 14.
                            ;;; The values can be changed from the interface according to user's preference

]

breed [ beekeepers beekeeper]  ; Beekeeper agent
breed [ loads load ]           ; Load agent

beekeepers-own [
  my_home                      ; Beekeeper's home location = patch from where a beekeeper is initialized
  my_postcode                  ; Postcode of the home patch - used only in varify the decision criteria e.g. identify postcodes for
                               ; beekeepers with no movement
  num_loads                    ; Number of loads a beekeeper owns
  my_loads                     ; Identifier of individual beekeeper's loads
  commercial?                  ; Determine wheather a beekeeper is commercial or non commercial
  split_number                 ; Number of time beekeepers split loads to find target cluster
  potential_targets            ; Patchset with available forage and not currently in use by any load
  my_targets                   ; Patchset (a subset of potential_targets) chosen by individual beekeepers after applying decision criteria
  reftarget                    ; One patch randomly selected from my_targets of beekeeper as a reference to finalize optimum forage locations
                               ; for each load (1patch=1load)
  distance_this_tick           ; Euclidean distance travelled during current time step
  shifting                     ; Average number of times hives moved
  total_distance_travelled     ; Sum of Euclidean distance travelled in each time step
  No_target_found              ; Count of number of times a beekeeper could not find desired target - used only in varify the migration patterns
]
loads-own [
  load_id                      ; Identifier for the owner beekeeper
  my_forage_cell               ; Patch for load to migrate in current time step selected according to load owner’s decision
  move_count                   ; Counter for load movement
  visited?                     ; Indicates whether owner beekeeper has visited the load
]

patches-own [
  postcode                    ; Postcode of patches

  jan feb mar apr may jun jul aug sep oct nov dec
  ; Patch variables for each month to read monthly forage availability raster value

  janP febP marP aprP mayP junP julP augP sepP octP novP decP
  ; Patch variables for each month to read monthly availability of premium species
  availability_months         ; Boolean values of forage availability for 12 months
  available_forage            ; Indicate whether forage is available in current time step
  sp_rich                     ; List of raster values of forage availability for 12 months
  richness                    ; Raster value for current timestep
  high_rich?                  ; True if value for richness variable is greater than or equal to three
  sp_premium_months           ; Boolean values of premium availability for 12 months
  sp_premium                  ; Value of avilability of premium species in current time step
  premium?                    ; Boolean values indicating whether premium species is available in current time step
  harvest_count               ; A number of times a patch is used during simulation run
]
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;Setup Procedure;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to setup_environment
  ca
  set num_months 12
  setup_study_area
  setup_beekeepers
  setup_loads
  setup_forage_availability_scenario
  reset-ticks
```

```
end

to setup_study_area

  set study_area gis:load-dataset  "Data/Study_area.shp"
  set res_town gis:load-dataset "Data/Validation_beekeeper_postcode.shp"
  gis:set-drawing-color grey
  gis:draw study_area 1
  gis:set-drawing-color grey
  gis:draw res_town 1

  ;;; Create patch set of patches that intersect study area. This will improve model speed by running code to only patches within study area

  set model_patches patches gis:intersecting study_area
  gis:set-coverage-minimum-threshold 0.0000001
  gis:apply-coverage res_town "POA" postcode
  ask model_patches [  ifelse (postcode <= 0) or (postcode >= 0)  [ ] [ set postcode 0]  ]   ; NaN fix

end

to setup_beekeepers
  let respatches model_patches with [postcode > 0 ]
  ask respatches [
    set postcode round (postcode)
  ]
  ;;; create turtles based on shapefile attributes
  foreach gis:feature-list-of res_town [ vector-feature ->
    ask up-to-n-of (gis:property-value vector-feature "POP_SEMI") respatches with [ postcode = (gis:property-value vector-feature "POA")]
    [sprout-beekeepers 1 [
      set shape "person"
      set size 16
      set my_home patch-here
      set my_postcode [postcode] of patch-here
      set commercial? false
      set color yellow
      set num_loads one-of [ 1 2 3 4 ]

      ;set num_loads 4              ;;;;;;;; to test the difference/simlarity between beekeepers with 4 and 5 loads.
    ]]
    ask up-to-n-of (gis:property-value vector-feature "POP_COM") respatches with [ postcode = (gis:property-value vector-feature "POA")]
    [sprout-beekeepers 1 [
      set shape "person"
      set size 16
      set my_home patch-here
      set my_postcode [postcode] of patch-here
      set commercial? true
      set color yellow
      set num_loads one-of [ 5 6 7 8 9 10 11 12 13 14 15]

      ;set num_loads 5             ;;;;;;;; to test the difference/simlarity between beekeepers with 4 and 5 loads.
      ]
    ]
  ]

end
to setup_loads
  ask beekeepers [
    hatch-loads num_loads [
      set shape "box"
      set size [size] of myself  * 0.2
      pen-up
      set load_id [ who ] of myself
      set my_forage_cell [my_home] of myself
    ]
    set my_loads loads with [ load_id = [who] of myself ]
  ]
end

to setup_forage_availability_scenario

  ifelse ( forage_availability_scenario = "random" )
  [ grow_random_forage ]
  [ read-scenario-from-data
    apply_forage_raster
    setup_monthly_forage_availability
  ]

end

to read-scenario-from-data
  ifelse ( forage_availability_scenario = "baseline" )

  [ set jan_availability gis:load-dataset "Data/Forage_availability/janc.asc"   ;;; set file path for GIS dataset
    set feb_availability gis:load-dataset "Data/Forage_availability/febc.asc"   ;;; set file path for GIS dataset
    set mar_availability gis:load-dataset "Data/Forage_availability/marc.asc"   ;;; set file path for GIS dataset
    set apr_availability gis:load-dataset "Data/Forage_availability/aprc.asc"   ;;; set file path for GIS dataset
    set may_availability gis:load-dataset "Data/Forage_availability/mayc.asc"   ;;; set file path for GIS dataset
    set jun_availability gis:load-dataset "Data/Forage_availability/junc.asc"   ;;; set file path for GIS dataset
    set jul_availability gis:load-dataset "Data/Forage_availability/julc.asc"   ;;; set file path for GIS dataset
    set aug_availability gis:load-dataset "Data/Forage_availability/augc.asc"   ;;; set file path for GIS dataset
    set sep_availability gis:load-dataset "Data/Forage_availability/sepc.asc"   ;;; set file path for GIS dataset
    set oct_availability gis:load-dataset "Data/Forage_availability/octc.asc"   ;;; set file path for GIS dataset
    set nov_availability gis:load-dataset "Data/Forage_availability/novc.asc"   ;;; set file path for GIS dataset
    set dec_availability gis:load-dataset "Data/Forage_availability/decc.asc"   ;;; set file path for GIS dataset

    ;;; reading baseline premium rasters

    set JanP_data gis:load-dataset "Data/Forage_availability/janpc.asc"
    set FebP_data gis:load-dataset "Data/Forage_availability/febpc.asc"
    set MarP_data gis:load-dataset "Data/Forage_availability/marpc.asc"
    set AprP_data gis:load-dataset "Data/Forage_availability/aprpc.asc"
    set MayP_data gis:load-dataset "Data/Forage_availability/maypc.asc"
    set JunP_data gis:load-dataset "Data/Forage_availability/junpc.asc"
    set JulP_data gis:load-dataset "Data/Forage_availability/julpc.asc"
```

```
    set AugP_data gis:load-dataset "Data/Forage_availability/augpc.asc"
    set SepP_data gis:load-dataset "Data/Forage_availability/seppc.asc"
    set OctP_data gis:load-dataset "Data/Forage_availability/octpc.asc"
    set NovP_data gis:load-dataset "Data/Forage_availability/novpc.asc"
    set DecP_data gis:load-dataset "Data/Forage_availability/decpc.asc"

  ]
  [ set-futures ]

end


To set-futures

  ifelse (forage_availability_scenario = "future (RCP6.0)" )

  [ ;;; setup future monthly forage availability from GIS data.
    set jan_availability gis:load-dataset "Data/Forage_availability/janf.asc"   ;;; set file path for GIS dataset
    set feb_availability gis:load-dataset "Data/Forage_availability/febf.asc"   ;;; set file path for GIS dataset
    set mar_availability gis:load-dataset "Data/Forage_availability/marf.asc"   ;;; set file path for GIS dataset
    set apr_availability gis:load-dataset "Data/Forage_availability/aprf.asc"   ;;; set file path for GIS dataset
    set may_availability gis:load-dataset "Data/Forage_availability/mayf.asc"   ;;; set file path for GIS dataset
    set jun_availability gis:load-dataset "Data/Forage_availability/junf.asc"   ;;; set file path for GIS dataset
    set jul_availability gis:load-dataset "Data/Forage_availability/julf.asc"   ;;; set file path for GIS dataset
    set aug_availability gis:load-dataset "Data/Forage_availability/augf.asc"   ;;; set file path for GIS dataset
    set sep_availability gis:load-dataset "Data/Forage_availability/sepf.asc"   ;;; set file path for GIS dataset
    set oct_availability gis:load-dataset "Data/Forage_availability/octf.asc"   ;;; set file path for GIS dataset
    set nov_availability gis:load-dataset "Data/Forage_availability/novf.asc"   ;;; set file path for GIS dataset
    set dec_availability gis:load-dataset "Data/Forage_availability/decf.asc"   ;;; set file path for GIS dataset

    ;;; reading premium rasters

    set JanP_data gis:load-dataset "Data/Forage_availability/janpf.asc"
    set FebP_data gis:load-dataset "Data/Forage_availability/febpf.asc"
    set MarP_data gis:load-dataset "Data/Forage_availability/marpf.asc"
    set AprP_data gis:load-dataset "Data/Forage_availability/aprpf.asc"
    set MayP_data gis:load-dataset "Data/Forage_availability/maypf.asc"
    set JunP_data gis:load-dataset "Data/Forage_availability/junpf.asc"
    set JulP_data gis:load-dataset "Data/Forage_availability/julpf.asc"
    set AugP_data gis:load-dataset "Data/Forage_availability/augpf.asc"
    set SepP_data gis:load-dataset "Data/Forage_availability/seppf.asc"
    set OctP_data gis:load-dataset "Data/Forage_availability/octpf.asc"
    set NovP_data gis:load-dataset "Data/Forage_availability/novpf.asc"
    set DecP_data gis:load-dataset "Data/Forage_availability/decpf.asc"
  ]
  [ ;; This is High emmission scenario
    ;;; setup future monthly forage availability from GIS data.
    set jan_availability gis:load-dataset "Data/Forage_availability/JanF1.asc"   ;;; set file path for GIS dataset
    set feb_availability gis:load-dataset "Data/Forage_availability/FebF1.asc"   ;;; set file path for GIS dataset
    set mar_availability gis:load-dataset "Data/Forage_availability/MarF1.asc"   ;;; set file path for GIS dataset
    set apr_availability gis:load-dataset "Data/Forage_availability/AprF1.asc"   ;;; set file path for GIS dataset
    set may_availability gis:load-dataset "Data/Forage_availability/MayF1.asc"   ;;; set file path for GIS dataset
    set jun_availability gis:load-dataset "Data/Forage_availability/JunF1.asc"   ;;; set file path for GIS dataset
    set jul_availability gis:load-dataset "Data/Forage_availability/JulF1.asc"   ;;; set file path for GIS dataset
    set aug_availability gis:load-dataset "Data/Forage_availability/AugF1.asc"   ;;; set file path for GIS dataset
    set sep_availability gis:load-dataset "Data/Forage_availability/SepF1.asc"   ;;; set file path for GIS dataset
    set oct_availability gis:load-dataset "Data/Forage_availability/OctF1.asc"   ;;; set file path for GIS dataset
    set nov_availability gis:load-dataset "Data/Forage_availability/NovF1.asc"   ;;; set file path for GIS dataset
    set dec_availability gis:load-dataset "Data/Forage_availability/DecF1.asc"   ;;; set file path for GIS dataset

    ;;; reading premium rasters

    set JanP_data gis:load-dataset "Data/Forage_availability/JanFP1.asc"
    set FebP_data gis:load-dataset "Data/Forage_availability/FebFP1.asc"
    set MarP_data gis:load-dataset "Data/Forage_availability/MarFP1.asc"
    set AprP_data gis:load-dataset "Data/Forage_availability/AprFP1.asc"
    set MayP_data gis:load-dataset "Data/Forage_availability/MayFP1.asc"
    set JunP_data gis:load-dataset "Data/Forage_availability/JunFP1.asc"
    set JulP_data gis:load-dataset "Data/Forage_availability/JulFP1.asc"
    set AugP_data gis:load-dataset "Data/Forage_availability/AugFP1.asc"
    set SepP_data gis:load-dataset "Data/Forage_availability/SepFP1.asc"
    set OctP_data gis:load-dataset "Data/Forage_availability/OctFP1.asc"
    set NovP_data gis:load-dataset "Data/Forage_availability/NovFP1.asc"
    set DecP_data gis:load-dataset "Data/Forage_availability/DecFP1.asc"
  ]
end


to grow_random_forage
  ;;;;; This scenario is included to run the model without specific forage availability data.
  ;;;;; This scenario is not included in the analysis presented in this paper.

  ask model_patches [

    set jan random 9
    set feb random 9
    set mar random 9
    set apr random 9
    set may random 9
    set jun random 9
    set jul random 9
    set aug random 9
    set sep random 9
    set oct random 9
    set nov random 9
    set dec random 9

    ;;;;;; Restrict the occurrance of premium species to specific region of the study area.;;;;;;;;;

    ifelse (pxcor < 220) and (pycor < 330) [
      set janP random 2
      set febP random 2
      set marP random 2
      set aprP random 2
```

```
      set mayP random 2
      set junP random 2
      set julP random 2
      set augP random 2
      set sepP random 2
      set octP random 2
      set novP random 2
      set decP random 2
    ]
    [ set janP 0
      set febP 0
      set marP 0
      set aprP 0
      set mayP 0
      set junP 0
      set julP 0
      set augP 0
      set sepP 0
      set octP 0
      set novP 0
      set decP 0
    ]

  ]

end


to apply_forage_raster ;;; apply raster values to patch variables

  gis:set-world-envelope (gis:envelope-union-of (gis:envelope-of jan_availability )
    ( gis:envelope-of study_area)
    (gis:envelope-of res_town))

  gis:apply-raster jan_availability jan
  gis:apply-raster feb_availability feb
  gis:apply-raster mar_availability mar
  gis:apply-raster apr_availability apr
  gis:apply-raster may_availability may
  gis:apply-raster jun_availability jun
  gis:apply-raster jul_availability jul
  gis:apply-raster aug_availability aug
  gis:apply-raster sep_availability sep
  gis:apply-raster oct_availability oct
  gis:apply-raster nov_availability nov
  gis:apply-raster dec_availability dec

  ;; apply premium raster

  gis:apply-raster JanP_data janP
  gis:apply-raster FebP_data febP
  gis:apply-raster MarP_data marP
  gis:apply-raster AprP_data aprP
  gis:apply-raster MayP_data mayP
  gis:apply-raster JunP_data junP
  gis:apply-raster JulP_data julP
  gis:apply-raster AugP_data augP
  gis:apply-raster SepP_data sepP
  gis:apply-raster OctP_data octP
  gis:apply-raster NovP_data novP
  gis:apply-raster DecP_data decP

end

to setup_monthly_forage_availability


  set forage_model_patches patches with [
    jan > 0 or  feb > 0 or  mar > 0 or apr > 0 or may > 0 or jun > 0 or jul > 0 or aug > 0 or sep > 0 or oct > 0 or nov > 0 or dec > 0 ]

  ask forage_model_patches [
    set harvest_count 0

    set availability_months [ ]
    set sp_rich [ ]
    set sp_premium_months [ ]

    ifelse aug > 0 or augP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (aug) sp_rich set sp_premium_months lput (augP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput  0 sp_premium_months]
    ifelse sep > 0 or sepP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (sep) sp_rich set sp_premium_months lput (sepP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput  0 sp_premium_months]
    ifelse oct > 0 or octP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (oct) sp_rich set sp_premium_months lput (octP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput 0 sp_premium_months]
    ifelse nov > 0 or novP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (nov) sp_rich set sp_premium_months lput (novP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput 0 sp_premium_months]
    ifelse dec > 0 or decP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (dec) sp_rich set sp_premium_months lput (decP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput 0 sp_premium_months]
    ifelse jan > 0 or janP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (jan) sp_rich set sp_premium_months lput (janP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput 0 sp_premium_months]
    ifelse feb > 0 or febP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (feb) sp_rich set sp_premium_months lput (febP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput 0 sp_premium_months]
    ifelse mar > 0 or marP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (mar) sp_rich set sp_premium_months lput (marP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput 0 sp_premium_months]
    ifelse apr > 0 or aprP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (apr) sp_rich set sp_premium_months lput (aprP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput 0 sp_premium_months]
```

```
    ifelse may > 0 or mayP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (may) sp_rich set sp_premium_months lput (mayP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput 0 sp_premium_months]
    ifelse jun > 0 or junP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (jun) sp_rich set sp_premium_months lput (junP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput 0 sp_premium_months]
    ifelse jul > 0 or julP > 0
    [set availability_months lput 1 availability_months set sp_rich lput (jul) sp_rich set sp_premium_months lput (julP) sp_premium_months]
    [set availability_months lput 0 availability_months set sp_rich lput 0 sp_rich set sp_premium_months lput 0 sp_premium_months]
  ]

end




;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;; go Procedure;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to go
 ask beekeepers [ set split_number 0 ]
  if (ticks < 1) [ reset-timer]  ;; check execution time for wach procedure
  if ticks = num_months [
    ask beekeepers [
      move-to my_home
      ask my_loads [ move-to [my_home] of myself ]
    ]
    store_output
    write-distance-to-csv
    show (word "execution finished in "timer" seconds" )
    stop  ]

  update_forage_availability
  update_targets
  migrate

  tick
end

to store_output
  let harvested_patches gis:patch-dataset harvest_count
  let filename (word "h_c_" behaviorspace-run-number "_" forage_availability_scenario ".asc")
  gis:store-dataset harvested_patches filename
end

to write-distance-to-csv
  ; we use the `of` primitive to make a list of lists and then
  ; use the csv extension to write that list of lists to a file.
  ;let filename1 (word "OutpuValidation" behaviorspace-run-number ".csv")
  csv:to-file "OutpuValidation.csv" [ (list commercial? num_loads my_postcode shifting total_distance_travelled distance_this_tick no_target_found) ]
end

to update_forage_availability

  ask forage_model_patches [
    set available_forage item ticks availability_months
    set richness item ticks sp_rich
    set sp_premium item ticks sp_premium_months
    ifelse available_forage = 0 [
      set pcolor black
    ][
      set pcolor 58
    ]

    ifelse sp_premium = 0 [
      set premium? false
    ] [
      set premium? true
      ;set pcolor blue
    ]

    ifelse richness >= 3 [
      set high_rich? true
    ] [
      set high_rich? false
    ]
  ]

end

to update_targets
  ask beekeepers [ pick_new_target ]
end

to pick_new_target
  ;;; Beekeeper chooses nearby patch, prioritizing premium and rich patches
  ifelse commercial? = false [ set  potential_targets patches with [(available self) and (distance myself < proximity)]]
  [ set potential_targets patches with [(available self)] ]

  ;;;;;;;;;;;;;;;;;;;;;;;;;  decision criteria ;;;;;;;;;;;;;

  ifelse any? potential_targets [

    ( ifelse

      any? potential_targets with [ premium? = true] [
        set my_targets potential_targets with [ premium? = true]
      ]

      any? potential_targets with [ high_rich? = true] [
        set my_targets potential_targets with [ high_rich? = true]
      ]
```

```
      [ set my_targets potential_targets ]
    )
    set reftarget one-of my_targets

  ][
    ;;; if beekeepers can not find any potential targets they move back home and start over
    move-to my_home
    set No_target_found No_target_found + 1
    ask my_loads [ move-to [my_home] of myself]
    set reftarget my_home
  ]

  set split_number split_number + 1

end

to migrate
  ask loads [ relocate ]
  ask beekeepers [ travel ]
end

to relocate
  let bkpr beekeeper load_id ;; identifying beekeeper of load using loadid
  let target [reftarget] of bkpr
  let open_spots patches with [ (patch_distance self target < spread) AND (available self) ]

  ( ifelse
    any? open_spots with [ premium? = true ] [
      set open_spots open_spots with [ premium? = true ]
    ]

    any? open_spots with [ high_rich? = true ] [
      set open_spots open_spots with [ high_rich? = true ]
    ]

  )

  if [available_forage] of patch-here = 0 or any? other loads-here  [
    ; beekeeepers with more than one load migrate when forage becomes unavailable, this maintains one load per patch rule
    ifelse (any? open_spots) [
      set my_forage_cell one-of open_spots
    ] [
      ifelse [split_number] of bkpr < 2
      [
        ask bkpr [ pick_new_target ]
        relocate
      ] [
        set my_forage_cell [my_home] of bkpr
      ]
    ]
    move-to my_forage_cell
    set move_count move_count + 1
    set harvest_count harvest_count + 1
  ]

end

to travel  ;Travels to loads one at a time, uses the nearest-neighbor algorithm
  set distance_this_tick 0
  ask my_loads [ set visited? FALSE ]
  let unvisited_loads my_loads with [ visited? = FALSE ]

  while [any? unvisited_loads] [
    let closest_load min-one-of unvisited_loads [ distance myself ]
    set distance_this_tick distance_this_tick + distance closest_load
    move-to closest_load
    ask closest_load [ set visited? TRUE ]
    set unvisited_loads unvisited_loads with [ visited? = FALSE ]
  ]

  set shifting mean [move_count] of my_loads
  set total_distance_travelled total_distance_travelled + distance_this_tick

end

;;;reporters

to-report available [pch]
  ifelse ([pcolor] of pch = 58) AND (not any? loads-here)
  [report true]
  [report false]
end

to-report patch_distance [ pch1 pch2 ]
  let x1 [pxcor] of pch1
  let y1 [pycor] of pch1

  let x2 [pxcor] of pch2
  let y2 [pycor] of pch2

  let xdiff x1 - x2
  let ydiff y1 - y2

  report sqrt (xdiff ^ 2 + ydiff ^ 2)
end


;;;;;;;;;;;;;;;;;;; output reporters used in behaviourspace experiment to understand hive migration patterns ;;;;;;;;;;;;;;;;;

to-report beekeepers_with_no_target
  report count beekeepers with [ No_target_found > 0 ]
end

to-report mean_travel_commercial
```

```
  report (mean [total_distance_travelled] of beekeepers with [commercial? = true] )
end

to-report min_travel_commercial
  report (min [total_distance_travelled] of beekeepers with [commercial? = true] )
end
to-report max_travel_commercial
  report (max [total_distance_travelled] of beekeepers with [commercial? = true] )
end

to-report std_travel_commercial
  report (standard-deviation [total_distance_travelled] of beekeepers with [commercial? = true] )
end

to-report mean_travel_semi_commercial
  report (mean [total_distance_travelled] of beekeepers with [commercial? = false] )
end
to-report min_travel_semi_commercial
  report (min [total_distance_travelled] of beekeepers with [commercial? = false] )
end
to-report max_travel_semi_commercial
  report (max [total_distance_travelled] of beekeepers with [commercial? = false] )
end
to-report std_travel_semi_commercial
  report (standard-deviation [total_distance_travelled] of beekeepers with [commercial? = false] )
end

to-report mean_monthly_travel_commercial
  report (mean [distance_this_tick] of beekeepers with [commercial? = true] )
end

to-report min_monthly_travel_commercial
  report (min [distance_this_tick] of beekeepers with [commercial? = true] )
end
to-report max_monthly_travel_commercial
  report (max [distance_this_tick] of beekeepers with [commercial? = true] )
end

to-report std_monthly_travel_commercial
  report (standard-deviation [distance_this_tick] of beekeepers with [commercial? = true] )
end

to-report mean_monthly_travel_semi_commercial
  report (mean [distance_this_tick] of beekeepers with [commercial? = false] )
end
to-report min_monthly_travel_semi_commercial
  report (min [distance_this_tick] of beekeepers with [commercial? = false] )
end
to-report max_monthly_travel_semi_commercial
  report (max [distance_this_tick] of beekeepers with [commercial? = false] )
end
to-report std_monthly_travel_semi_commercial
  report (standard-deviation [distance_this_tick] of beekeepers with [commercial? = false] )
end

to-report mean_shifting_commercial
  report (mean [shifting] of beekeepers with [commercial? = true] )
end

to-report mean_shifting_semi_commercial
  report (mean [shifting] of beekeepers with [commercial? = false] )
end

to-report min_shifting_commercial
  report (min [shifting] of beekeepers with [commercial? = true] )
end

to-report min_shifting_semi_commercial
  report (min [shifting] of beekeepers with [commercial? = false] )
end

to-report max_shifting_commercial
  report (max [shifting] of beekeepers with [commercial? = true] )
end

to-report max_shifting_semi_commercial
  report (max [shifting] of beekeepers with [commercial? = false] )
end


to-report mean_shifting_beekeepers
  report (mean [shifting] of beekeepers )
end

to-report min_shifting_beekeepers
  report (min [shifting] of beekeepers )
end

to-report max_shifting_beekeepers
  report (max [shifting] of beekeepers )
end
```

Note: An early version of the Beehive migration ABM is available at NetLogo modelling commons: http://modelingcommons.org/browse/one_model/6959#model_tabs_browse_info.
This version does not involve any data but still provide a proof of concept for the hive migration decisions. In this version, the agents and environment are randomly created.

APPENDIX 7 - COMPLETE MODEL DESCRIPTION FOR THE HIVE MIGRATION ABM [1] INTEGRATED WITHIN THE B-Agent

Appendix A in the submission in review with Applied Geography - Patel, V., E. M. Biggs, N. Pauli, and B. Boruff. 2023. Assessing the influence of variation in forage availability on spatial patterns of beehive migration using a hybrid modelling approach - *B-Agent*

Table 7.1. Detailed model description for the hive migration ABM following ODD+D guiding format provided in (Müller et al., 2013).

Outline		Guiding questions	ODD+2D Model description
I) Overview	I.i Purpose	I.i.a What is the purpose of the study?	The overall purpose of the hive migration ABM is to understand how the variability in spatial patterns of forage availability may influence beehive migration decisions and associated patterns. Specifically, it aims to answer three questions: • What are the spatial patterns of forage locations harvested by beekeepers for baseline and future forage availability? • - What is the annual average distance travelled by beekeepers for baseline and future forage availability? • - What is the frequency of beehive migration for baseline and future forage availability? The model implements a human decision model developed from stakeholder interviews on a spatially explicit landscape for selecting suitable apiary site locations for beehive migration.
		I.ii.b For whom is the model designed?	Beekeepers - to optimize beehive migration decisions. Land managers - to understand important forage area targeted by beekeepers.
	I.ii Entities, state variables, and scales	I.ii.a What kinds of entities are in the model?	There are two types of agents: i. Beekeepers: each beekeeper agent acts independently from each other. Each beekeeper is characterised as a commercial or a semi-commercial beekeeper, each following a specific set of decision rules. ii. Loads (of beehives): load agents are designed as a non-cognitive agent. Each load is linked to their owner beekeeper agent and follows their beekeeper agent's decision rules for movement. The environment is represented as spatial grid cells representing the distribution of bee forage species targeted by beekeepers.
		I.ii.b By what attributes (i.e., state variables and parameters) are these entities characterised?	See Table A.2. for full details regarding entities, state variables and parameters. **Beekeeper agent:** *my_home, num_loads, my_loads, commercial?, potential_targets, reftarget, my_target, distance_this_tick, total_distance_travelled, Shifting, No_target_found* **Load agent:**

			Load_id, my_forage_cell, move_count, visited? **Patches (cells):** *available_forage, sp_rich, premium?, availability_months, richness sp_premium _months, sp_premium, high_rich?, harvest_count jan, feb, mar, apr, may, jun, jul, aug, sep, oct, nov, dec, janP, febP, marP, aprP, mayP, junP, julP, augP, sepP, octP, novP, decP*
		I.ii.c What are the exogenous factors / drivers of the model?	The forage availability scenario is developed using 19 bioclimate variables prepared for current (1976 – 2005) and future (2015 – 2085) climate for Australia.
		I.ii.d If applicable, how is space included in the model?	In this spatially explicit ABM, the space is represented using vector and raster GIS data. Vector data of the study area boundary is used to extract cells for the study area (*model_patches).* Vector data for postcode boundaries is included to initialise the beekeeper agent from their home residential location (a random cell allocation within the home postcode boundary). Raster grid cells build forage availability for each time step.
		I.ii.e What are the temporal and spatial resolutions and extents of the model?	One time step represents one month and the simulations are run for one year using each forage availability scenario (baseline and future). One grid cell represents a ground area of 9 km^2 with the total study area coverage at 478,400 km2 (SWWA).
	I.iii Process overview and schedulin g	I.iii.a What entity does what, and in what order?	• Model initialisation: – setup beekeeper agents (number of loads, residential location), – setup load agents (identifier load_id, location) – setup environment (study area patches, residential patches, forage patches) • Each time step – All patches: *update_forage_availability* – All beekeepers: execute *update_targets* sub-model. If can't find suitable targets for all their loads, split their loads (set *split_number* to 1) and find suitable target for each split. If still can't find suitable target, move back home. Size of loads in splitted cluster depends on the number of forage sites found within each cluster. – All loads and beekeepers: execute *migrate* sub-model*,* where loads *relocate* and beekeepers *travel.* – There is no mortality included in this hive migration ABM; the number of agents and their characteristics (e.g., commercial or semi-commercial beekeepers) remain constant during each run. – Interactions between individual beekeeper agents are also not included

II) Design Concepts	II.i Theoretical and Empirical Background	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?	The model is built based on social-ecological system (SES) theory, with the focus on beehive migration as one of the key social-ecological interactions. The model assumes a common property resource use i.e., each forage patch is accessible to each beekeeper. The model only includes the components that are essential in understanding the interplay of the change in forage availability and decision-making of beekeepers to assess the socio-economic performance measures (one of the outcomes of the beekeeping SES as identified in (Patel et al., 2020)) at the SES level. Simple decision rules followed by beekeepers become complex when the decision-making is done at the individual load level, which requires the implementation of the beekeeper decision model according to the change in local environment of each individual load during each time step. • Forage site selection is based on the decision-making rules followed by beekeeper agents. • The travel procedure of beekeepers includes visiting one load (patch) at a time following the nearest-neighbour algorithm. • The travel distance between two patches is calculated by summing the Euclidean distances between current patch and the target patch for each new patch in the migration sequence.
		II.i.b On what assumptions is/are the agents' decision model(s) based?	The theoretical basis for beekeeper decision models reflects satisficing heuristics in bounded rationality (Todd and Gigerenzer, 2000). Satisficing heuristics assumes that the decision maker has knowledge of all feasible possibilities for the current timestep (Todd and Gigerenzer, 2000). Satisficing heuristics is commonly used in sequential search where, an individual establishes a set of aspirational criteria and terminates their search for alternatives when met the criteria (Schilirò, 2018; Todd & Gigerenzer, 2000). Specific decision criteria have been prepared using stakeholder interview data.
		II.i.c Why is a/are certain decision model(s) chosen?	The model represents beehive migration as a social-ecological interaction where movement is driven by the decision-making rules followed by beekeeper agents. One of the main reasons to prepare a heuristic decision model using empirical data is inadequate data availability to apply a utility function or a preference function of each cell. Data on flowering times for each forage species were also available as monthly flowering therefore, the movement decisions are based on simple Boolean logic e.g., flowering available = 1 no flowering = 0. Honey production data was available at very broad scale and only reflected a fraction of honey producers in the state. Historic beehive migration data shared by some stakeholders contained limited information for use in a spatially explicit model.
		II.i.d If the model / a submodel (e.g., the decision model) is based on empirical data, where do the data come from?	Factors contributing to apiary site selection by beekeepers and important forage species targeted for nectar and pollen are ascertained using interview data from 29 beekeepers.

			Spatial data related to key bee forage species per apiary permit location are collected using participatory mapping in GIS. Additional spatial locations for key bee forage species are downloaded from the Atlas of Living Australia (https://spatial.ala.org.au). See Input data section for further details about data.
		II.i.e At which level of aggregation were the data available?	Aggregation of data was done mainly to maintain confidentiality of the participants. For example, Beekeepers' residential locations are aggregated at the postcode level.
	II.ii Individual Decision Making	II.ii.a What are the subjects and objects of decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision making included?	- Beekeepers are the subject of decision-making. The object is relocating loads between forage cells. - Loads are designed as non-cognitive agents that follow the decision model of their owner beekeeper agent. There is only one level of decision-making at the individual (beekeeper agent) level.
		II.ii.b What is the basic rationality behind agents' decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	The model assumes that the beekeeper agents know of all feasible options about their forage environment for the current time step. Beekeeper agents' decision-making follows satisficing heuristics in bounded rationality. Beekeeper agents follow three success criteria to decide the best possible option for migrating their loads. In most beekeeping systems, beekeepers usually have a planned sequence of forage sites (Pilati and Fontana, 2018). However, unlike agriculture systems, beekeeping on high species diversity natural landscapes increases complexities in implementing planned behaviour in data-poor systems. Therefore, knowledge about the world other than current time step (i.e. next time step) is not implemented in this version of the model, which does not allow beekeeper agents to plan for a sequence of forage sites.
		II.ii.c How do agents make their decisions?	- Beekeeper agents follow if-then rules, e.g., if (available_forage = 0), then… - To select specific target cells, beekeeper agents use an iterative selection process. Beekeeper agents aim to minimise their travel and first prioritise sites with premium species (i.e., species with high economic return). If *premium species* are not available, then the second priority are sites with *high species richness*. In the case that neither of these priorities are available, beekeeper agents choose any site with forage resource available. Beekeeper agents find the best option to maximise their gain from each individual forage site. Maximised gain from a migration sequence as accessing a cluster of sites may reduce inter-load travel.
		II.ii.d Do the agents adapt their behaviour to changing endogenous and exogenous	Yes. Beekeeper agents migrate their hives to different forage patches according to the availability and quality of forage in each time step.

		state variables? And if yes, how?	
		II.ii.e Do social norms or cultural values play a role in the decision-making process?	No. The decision-making occurs at an individual level (beekeeper agent) and is based on interview data. The decision processes in the model are not representing social norms and cultural values.
		II.ii.f Do spatial aspects play a role in the decision process?	Yes, the forage patches read monthly forage availability from raster data. Beekeeper agents are initialised from patches within the polygon boundary of postcodes. The *proximity* determines the area that a semi-commercial beekeeper agent can move in the next step. The *spread* determines maximum preferred distance between each individual load of a beekeeper agent. (See section IIIiii Input Data for further details)
		II.ii.g Do temporal aspects play a role in the decision process?	Yes, the state of forage availability changes every month. Decision-making is completely based on the forage availability in current time step. In addition, the model includes two temporal forage availability scenarios to understand the beekeepers forage-environment interplay for baseline and future modelled behaviour.
		II.ii.h To which extent and how is uncertainty included in the agents' decision rules?	Uncertainty is not included in the rules of the decision making model. However, model uncertainty is accounted for through running the simulation 100 times for each baseline and future forage availability scenarios.
	II.iii Learning	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?	No, individual learning is not included.
		II.iii.b Is collective learning implemented in the model?	No, collective learning is not implemented.
	II.iv Individual Sensing	II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions?	Beekeeper agents sense the state of the forage availability environment (values for *premium?, High-rich? richness, available_forage*) for the whole study area in the current time step. The sensing process is not erroneous as the forage availability environment is deterministic (i.e. the values for *premium?, High-rich? richness, available_forage)* remains the same in one time step .

		Is the sensing process erroneous?	
		II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?	Beekeeper agents are not able to sense state variables of other beekeepers. However, individual a beekeeper agent can see the state variables of their loads. Individual load agents can also see the state variables of their owner beekeepers.
		II.iv.c What is the spatial scale of sensing?	The spatial scale of environment is global i.e., beekeeper agents can sense the state of the environment for the whole study area. Sensing of agent loads occurs locally.
		II.iv.d Are the mechanisms by which agents obtain information modelled explicitly, or are individuals simply assumed to know these variables?	We assume that: i). Beekeepers can always sense the value of the sensed variables for the state of environment for themselves and their loads. ii). Loads, being non-cognitive agents, always have a sense of their owner's decision-making (e.g. beekeeper agent's *reftarget* and the value of *spread*.)
		II.iv.e Are costs for cognition and costs for gathering information inclu-ded in the model?	No costs for cognition or information gathering are included.
	II.v Individual Prediction	II.v.a Which data uses the agent to predict future conditions?	Agents (beekeepers and loads) do not predict future conditions.
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?	Not applicable.
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	Not applicable.
		II.vi.a Are interactions among agents and entities	Interactions between agents (beekeepers and loads) are direct. In the real world beekeeping system, beekeepers interact by moving their loads to the locations selected according to their decision-making model; beekeepers

	II.vi Interaction	assumed as direct or indirect?	also interact with their loads to check beehive performance on the forage site. We represent this direct interaction as only one movement as part of the *migrate* submodel.
		II.vi.b On what do the interactions depend?	The interactions depend on the state of the forage availability environment during each time step.
		II.vi.c If the interactions involve communication, how are such communications represented?	Not applicable.
		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?	Not applicable.
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect, and are affected by, the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?	Beekeeper agents do not form any collectives. Each load represents approximately 100 beehives. A sum of the loads owned by a beekeeper (*num_loads*) determines whether the beekeeper is *commercial*?. This influences the decision-making model for semi-commercial beekeepers (*commercial? = false*) by limiting their search to the value of *proximity* variable. The value for the number of beehives in each load and the cutoff value for (*num_loads*) to ascertain the *commercial*? state of the beekeepers has been identified from empirical data (see section IIIiii Input Data for further details).
		II.vii.b How are collectives represented?	Loads are represented as non-cognitive agents. The sum of loads is represented as a beekeeper variable (*num_loads*).
	II.viii Heterogeneity	II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?	Beekeeper agents' state variables are homogenous. Load agents' state variables are homogenous.

		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?	All beekeeper agents follow the same decision-making model to select quality forage sites for their loads. However, the value of the beekeeper's state variable *commercial?* adds a *proximity* filter if a beekeeper is not *commercial?*. Therefore, the decision-model becomes restricted to a subset of patches rather than the whole study area.
	II.ix Stochasticity	II.ix.a What processes (including initialization) are modeled by assuming they are random or partly random?	Initialisation of the beekeeper agents is partly random. The beekeepers are initialised from a random patch within the spatial boundary representing an area of a postcode within Western Australia (see section IIIiii Input Data for further details). The number of loads are randomly assigned to the beekeepers, which makes the *commercial?* state of beekeepers randomly distributed during each run. The movement of beekeepers is initiated in a random order. The order of movement is determined based onby resource condition on the a patch and the number of loads owned by a beekeeper agent. For example, a beekeeper agent moves if the patch has no resource available or the patch hasor inadequate resource available. The i.e., beekeepers may have more than one load requiring additional resources as the (the model assumes that the resources on one patch can only cater for one load).
	II.x Observation	II.x.a What data are collected from the ABM for testing, understanding, and analyzing it, and how and when are they collected?	The graphical user interface (GUI) of the model includes the following for each time step: Plots: • Relative travel distance - mean and standard deviation across all beekeepers - mean and standard deviation across all commercial beekeepers - mean and standard deviation across all semi-commercial beekeepers Monitors: • Annual migration - hive migration frequency *(shifting)* - mean across all beekeepers - mean and standard deviation across all commercial beekeepers - mean and standard deviation across all semi-commercial beekeepers • Harvested forage cells - *Harvest_count* of patches

		II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)	The key outcomes of the model are spatial patterns of beehive migration and the travel distances associated with each pattern. These outcomes emerge from beekeepers' decisions to select potential locations as forage sites and shifting their loads to selected forage sites. The results will also determine to what extent changing forage availability may affect travel distance associated with beehive migration under future forage availability.
III) Details	II.i Implementation Details	III.i.a How has the model been implemented?	The model has been implemented in NetLogo 6.2.0.
		III.i.b Is the model accessible and if so where?	Complete model code is provided as part of the Supplementary Information (SI 3).
	III.ii Initialization	III.ii.a What is the initial state of the model world, i.e., at time t=0 of a simulation run?	The initial state of the model includes the following initialisation procedures: - Import GIS data to setup study area and forage availability variables. - Initialise each beekeeper from a random home patch within the GIS boundary of postcodes. - Beekeepers initialise their loads according to the value of their *num_loads* variable (1 – 15) at their home patch. - The value of *load_id* is initialised to match the unique *who* number (A NetLogo inbuilt variable that initialises with the beekeeper agents representing unique id) to define an ownership relationship. See section III.iv Submodels for details about these procedures.
		III.ii.b Is initialisation always the same, or is it allowed to vary among simulations?	Initial forage availability varies based on the scenario selected for the simulation before the model run (e.g., *if* forage availability scenario is *'baseline',* the model imports the baseline forage availability raster, *else,* the model imports the raster representing *'future'* forage availability). The forage availability environment varies according to the imported raster data. Initialisation of the beekeeper agents varies partially i.e., on any randomly selected patch within the postcode boundary. Since the number of loads are randomly assigned to beekeeper agents, load agents' initial location also varies for each model simulation.
		III.ii.c Are the initial values chosen arbitrarily or based on data?	Initial values are chosen based on data (see next section for details).
	III.iii Input Data	III.iii.a Data Overview: does the model use input from external sources such as data files or other models to represent processes that change over time?	• Data used for the model come from various sources: • Primary data - collected using interviews and participatory mapping with industry stakeholders. • Responses for the following interview themes are used to prepare rules for selecting the forage species for beehive migration; shortlisting thirty bee forage species targeted by beekeepers and identifying premium species. • Factors considered for deciding forage location for hive migration. • Factors affecting hive migration decisions.

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Key target flora.
Costs associated with beekeeping.

Confidential data sourced from government agencies – ‘Beekeepers data’ including beekeepers’ residential location and hive holding (DPIRD) and Apiary permits spatial data including apiary permit coordinates and permit ownerships (DBCA).
Beekeepers’ hive holding data are used to differentiate between commercial (500 + hives) and semi-commercial beekeepers (0 – 499 hives). Beekeepers Residential postcodes are used to extract 88 postcodes from Australian postcodes dataset.
Apiary permit ownership data are used in participatory GIS mapping with 29 beekeepers to identify target species and forage availability months for each permit location. Participatory mapping results are then used to develop the monthly forage availability environment in the model.
Other data –
A Shapefile of Australia postcode boundaries was downloaded from the Australian Bureau of Statistics (ABS). A Shapefile of Interim Biogeographical Regions Australia (IBRA) was downloaded from https://www.data.wa.gov.au.
Species occurrence data for the 30 shortlisted species are downloaded using the spatial portal Atlas of living Australia [1] (https://spatial.ala.org.au). Occurrence records are clipped using study area boundary, which was prepared from spatial data for Interim Biogeographic Regionalisation for Australia (IBRA) (https://www.environment.gov.au/). Flowering times for 30 bee forage species are obtained from the Florabase https://florabase.dpaw.wa.gov.au. For the 2 premium species, peak flowering times are recorded from (French et al., 2019).
Participatory GIS mapping data was used to prepare additional species occurrence samples aiming to overcome spatial bias in ALA records (Fithian et al., 2015; James et al., 2018). Apiary permit locations are splitted based on the species targeted at each permit location to prepare additional occurrence records for each of the forage species listed in table 1 in the main text.
The National Vegetation Information System (NVIS) Version 6.0 data are downloaded from https://www.environment.gov.au. This dataset was used to mask cleared, non-native vegetation, and buildings from the forage availability raster.

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[1] Atlas of Living Australia (ALA) is a platform for providing open source biodiversity data covering over 85 million records of more than 111,000 species, aggregated from multiple sources and citizen science across Australia (ALA, 2020). Bias in ALA data has been recognised in the literature with the recommendations for approaches such as additional sampling and digitizing to overcome data quality gaps (James et al. 2018).

			• Data for Australia, current climate baseline (1976 – 2005) and Australia climate projection for RCP 6.0 GCM: CSIRO Mark 3.0 for 2055 ([Dataset] Vanderwal, 2012) are obtained from The Biodiversity Climate Change Virtual Laboratory (BCCVL, http://bccvl.org.au/). • From 2670 records in the Australia postcode dataset, 88 residential postcode polygons for beekeepers in Western Australia are extracted. The postcode boundaries are used to initialise the beekeeper population according to the number of beekeepers for each postcode boundary according to the beekeeper data. The value for their num_loads variable is also assigned according to the hive holding range mentioned for each of the beekeeper agents in the beekeeper data. Since a load size for different beekeepers ranges from 90 – 100 hives, the model assigns the num_loads value ranging from 1 – 4 for the beekeeper agents with the hive holding range of 50 – 499. Beekeeper agents with 500 or more hives (num_loads $\geq$ 5) are classified as commercial beekeepers (Patel et al., 2020). • From the IBRA Shapefile 18 subregions are dissolved to prepare the study area boundary for Southwest Western Australia (SWWA). • Occurrence data for the 30 bee forage species are updated with apiary permit locations as additional occurrence points for each of the 30 species. The species distribution for each bee forage species was prepared using species occurrence data (see the following section for further details).
	III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?	**Model setup** The model setup involves the following four functions: i) *setup_globals* – this function hardcodes the value for *num_months* as 12 (months). A user defined input value for the *proximity* is set as 300 and for the *spread* 20 is the initial value. These values are kept constant. However, the model interface allows the user to change the input values if required. ii) *setup_study_area* – this procedure imports GIS data including the study area and postcode boundaries, adjusts NetLogo world to match with the extent of GIS data, and sets the patch size to the same as the raster cell size(3000 $\times$ 3000). Two subsets of patches have been created: one representing patches that are contained within the study area boundary and another representing patches that are contained within the postcode boundary. These are created to simulate the model only within the selected study area. iii) *setup_beekeepers* – a number of commercial and semi-commercial beekeeper agents are initialised from within the postcode boundary based on their residential postcode from the beekeeper data. iv) *setup_loads* – load agents are initialised on the same patch as their owner beekeeper agent. The number of loads initialised per beekeeper agent is determined by the value of the *num_loads* variable (1 – 15) for each beekeeper agent. The value of the *num_load* variable is determined according to the beekeeper data.

1. *Forage availability submodel*

The forage availability submodel includes the following functions. Since the forage availability changes at every time step, the submodel represents two functions, one at the model setup stage (*setup_forage_availability_scenario)* and one during model run stage (*update_forage_availability*).

i) *setup_forage_availability_scenario* – each forage availability scenario includes 12 rasters representing the number of species flowering per pixel for each month. Preparation of these monthly raster involves the following process (see Figure 1 for the workflow):

a) 30 bee forage species are shortlisted from the beekeepers interview data.
b) Occurrence points for the shortlisted species are downloaded from the Atlas of Living Australia (ALA).
c) Additional occurrence points for each species was added using data collected from GIS-based participatory mapping conducted with individual beekeepers.
d) Combined occurrence points for each species are used in a MaxEnt (Phillips et al., 2006) species distribution model using 19 bioclimatic variables for the Australian current climate to obtain a habitat suitability distribution for each target species.
e) Then, step d was repeated using bioclimatic variables for Australian future climate data (see section IIIiii Input data for details).
f) The raster outputs of individual species distribution are refined by excluding cells with habitat suitability less than 0.5 (Freeman and Moisen, 2008)
g) The refined rasters are then combined according to their month of flowering using Python to obtain 12 rasters representing monthly forage availability i.e., the number of species flowering per month for each pixel for *baseline* and *future* forage availability scenario.
h) Step d – g are repeated using occurrence points for two premium species (*Eucalyptus marginata* and *Corymbia callophylla*) to prepare *baseline* and *future* forage availability of premium species.

Figure $A._1$: Workflow representing steps in creating forage availability scenario

The *setup_forage_availability_scenario* function also involves two sub-functions:

- *apply_forage_raster* - for each *baseline* and *future* forage availability scenario, values for the patch variables representing each month (*jan – dec*) and each premium month (*janP – decP*) are initialised from reading raster data corresponding to each forage availability scenario.

- *setup_monthly_forage_availability* – this function first prepares a subset of *model_patches* that have forage available (*forage_model_patches)* based on the values of *jan – dec* variables (e.g. *jan > 0… dec > 0*). Then creates three lists:
  - *sp_premium:* this list includes Boolean values (0 or 1) based on the raster value for (*janP – decP)*, where first value corresponds to August (*augP)*.
  - *sp_rich:* this list includes raster values (ranging from 0 – 9) for (*jan – dec)*, where the first value corresponds to August (*aug)*.
  - *availability_months:* This list includes Boolean values (0 or 1) based on raster value for (*jan – dec)*, where the first value correspond to August (*aug)*.

Model run

The model runs for 12 time steps (*num_months)*. Each time step involves running the following functions:

ii) update_forage_availability – This function first updates the forage characteristics for each patch and then identifies forage criteria for each patch that contributes to hive migration decision making. Further details about the procedures and specific patch variables are as follows:

Every time step, the *forage_model_patches* reads the values corresponding to the current time step (time step 1 = August) from the lists created by the *setup_monthly_forage_availability* function and updates the values for three patch variables as follows:

- The values for *available_forage* will be updated for the current time step from the *availability_months* list.
- The values for *richness* will be updated for the current time step from the *sp_rich* list.
- The values for will be updated for the current time step from the *sp_premium _months* list.
- The values for *premium?* will be updated as *false* if *sp_premium = 0; true* otherwise.
- The values for high_rich? will be updated as *false* if richness < 3 ; *true* otherwise.

2. Beekeeper's decision-making submodel

			i) This submodel represents the beekeeper agent's decision-making process for selecting apiary site locations to migrate their hives. The submodel involves the following functions: *update_targets* - in the beginning, if forage resources at the beekeeper agents' initial patch (*my_home)* becomes zero, all beekeeper agents execute *pick_new_targets* function. Since one forage patch can only serve one load, the beekeepers with more than one load find new forage sites despite having forage availability at their home patch. This function follows one load per patch rule. ii) *pick_new_targets* – This function represents the beekeeper agents finding new target locations to relocate their loads. - In each time step, each beekeeper agent identifies a set of patches (*potential_targets*) that has forage available (*available_forage = 1)* and not in use by any other beekeeper agent's load. Here, semi-commercial beekeepers agents limit their search according to the value of *proximity* variable. - A beekeeper agent who is unable to find any *potential_target* updates the value of the *no_targets_found* variable and moves back to *my_home.* Although, this decision involves additional travel, it doesn't give unrealistic travel distance associated with beehive migration as the model represent only one trip to the forage sites in contrast to the multiple trips (checking forage site before moving hives and checking hives on site). - A beekeeper agent with any *potential_targets* then evaluates their *potential_targets* using *if..then* rules as presented by the following pseudocode: ***If*** *any **potential_targets** are **premium?**... then update value for **my_targets** to just the **premium?** patches* ***else*** ***if*** *any **potential_targets** are **high_rich?** , update value for **my_targets** to just the **high_rich?** patches* ***else*** *update value for **my_targets** to any patches with **available_forage*** - Then beekeeper agents identify one patch as *reftarget* from the set of their target forage sites (*my_targets).* The *reftarget* acts as a reference for load agents to run their owner's decision model. ***3. Migrate submodel:***

			This submodel represents agent movement and calculates relative travel distance in the model. The submodel involves two functions *relocate_loads* and *travel_beekeeper* each representing movement of loads and beekeepers respectively. a) *relocate_loads*: in this function, load agents execute their beekeeper agent's decision model to locate to their destination patch. - Load agents move when the *available_forage* on their current patch becomes zero. - First, the loads temporarily set *target* as their owner beekeeper's *reftarget,* then search from *target* within the range of *spread* to identify *open_spots* as a set of empty (not in use by any other load) patches that has forage available (*available_forage = 1).* This process is similar to beekeeper agents finding *potential_targets.* - Load agents that can find any *open_spots* will run the above mentioned pseudocode to select *my_forage_cells.* - Load agents will move to *my_forage_cells* and update the value for *move_count* by 1 unit. - When beekeeper agents cannot find clustered targets for all loads at once, they search for two smaller clusters that can accommodate half (*split*) of their number of loads (num_loads) each and run *pick_new_target* function to find another *reftarget* for load agents to execute their *relocate* function. b). *travel_beekeepers:* this function represents a beekeeper agent's movement to each of their load's forage locations (*my_forage_cells).* - First, the beekeeper agent moves to their closest load from their reftarget and marks that load visited by setting visited? = true. This movement follows the nearest neighbour algorithm. The beekeepers repeat this movement until all loads are visited. - In each time step, beekeeper agents update their *distance_this_tick* variable by adding distance travelled during each time step. The travel distance is calculated as a Euclidean distance between two patches using the following equation. Every time step beekeepers updates total distance travelled as *total_distance_travelled = total_distance_travelled + distance_this_tick.* $d(P_1,P_2) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$ Eq. (A.1) Where, d = Euclidean distance between two patches P_1 = Current Patch P_2 = Target Patch x_1, y_1 = patch coordinates of current patch x_2, y_2 = patch coordinates of next patch

		III.iv.b What are the model parameters, their dimensions and reference values?	The details about model parameters, their values and data sources are provided in Table SI 2B.
		III.iv.c How were submodels designed or chosen, and how were they parameterized and then tested?	The beekeeper agents' decision-making submodels are designed based on primary data collected from beekeepers in WA. The decision-making of beekeepers models are tested for their ability to recreate the following patterns: i) The mean annual distance travelled for the commercial beekeepers is always higher than semi-commercial beekeepers. ii) The annual frequency of beehive migration (maximum shifting) ranges between two to six. iii) The number of forage sites used in the future increases in the inland regions of the state.

Table 7.2. Entities, state variables and parameters.

Variables / Parameters	Description	Possible Values / ranges/dataset	Data type	Source / reference
Global - Data describes global variables/parameters for the model				
res_town	Vector-data for beekeepers residential postcode	Shapefile of WA postcode	Vector - polygon	**https://catalogue.data.wa.gov.au
res_patches	NetLogo patches that are contained within the res_town boundary	Set of patch coordinates	Cells	-----
study_area	Vector-data for study area extracted from IBRA subregions shapefile	Shapefile of eighteen IBRA subregions	Vector - polygon	**https://catalogue.data.wa.gov.au
model_patches*	Patches intersecting study_area	Set of patch coordinates	Cells	-----
forage_model_patches*	Patches intersecting study_area that has flowering available_forage during any month of the year	Set of patch coordinates	Cells	-----
num_months	Number of months used to define model time step	12	Months	Authors' selection
jan_availability	Variable to read raster values representing distribution of bee forage species that flowers in January	0 – 9	Integer	Maximum value for forage availability output rasters
feb_availability	Variable to read raster values representing distribution of bee forage species that flowers in February	0 - 9	Integer	Maximum value for forage availability output rasters
mar_availability	Variable to read raster values representing distribution of bee forage species that flowers in March	0 - 9	Integer	Maximum value for forage availability output rasters

apr_availability	Variable to read raster values representing distribution of bee forage species that flowers in April	0 - 9	Integer	Maximum value for forage availability output rasters
may_availability	Variable to read raster values representing distribution of bee forage species that flowers in May	0 - 9	Integer	Maximum value for forage availability output rasters
jun_availability	Variable to read raster values representing distribution of bee forage species that flowers in June	0 - 9	Integer	Maximum value for forage availability output rasters
jul_availability	Variable to read raster values representing distribution of bee forage species that flowers in July	0 - 9	Integer	Maximum value for forage availability output rasters
aug_availability	Variable to read raster values representing distribution of bee forage species that flowers in August	0 - 9	Integer	Maximum value for forage availability output rasters
sep_availability	Variable to read raster values representing distribution of bee forage species that flowers in September	0 - 9	Integer	Maximum value for forage availability output rasters
oct_availability	Variable to read raster values representing distribution of bee forage species that flowers in October	0 - 9	Integer	Maximum value for forage availability output rasters
nov_availability	Variable to read raster values representing distribution of bee forage species that flowers in November	0 - 9	Integer	Maximum value for forage availability output rasters
dec_availability	Variable to read raster values representing distribution of bee forage species that flowers in December	0 - 9	Integer	Maximum value for forage availability output rasters
janP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in January	0 - 2	Integer	Maximum value for forage availability output rasters
febP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in February	0 - 2	Integer	Maximum value for forage availability output rasters

marP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in March	0 - 2	Integer	Maximum value for forage availability output rasters
aprP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in April	0 - 2	Integer	Maximum value for forage availability output rasters
mayP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in May	0 - 2	Integer	Maximum value for forage availability output rasters
junP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in June	0 - 2	Integer	Maximum value for forage availability output rasters
julP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in July	0 - 2	Integer	Maximum value for forage availability output rasters
augP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in August	0 - 2	Integer	Maximum value for forage availability output rasters
sepP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in September	0 - 2	Integer	Maximum value for forage availability output rasters
octP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in October	0 - 2	Integer	Maximum value for forage availability output rasters
novP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in November	0 - 2	Integer	Maximum value for forage availability output rasters
decP_data	Variable to read raster values representing distribution of premium bee forage species that flowers in December	0 - 2	Integer	Maximum value for forage availability output rasters
beekeeper_population	Number of beekeeper agents to be initialized	1 - 88	Integer	Beekeeper dataset
proximity	Maximum distance that beekeepers are willing to travel from their home location	300	Integer	Beekeeper interview data (max distance for semi-commercial

				beekeepers is 300km from their home location)
spread	Preference for maximum distance between individual loads	20 km	Integer	Beekeeper interview data and a GIS based point distance analysis of individual beekeepers apiary site clusters.
Beekeeper Agents				
my_home	Patch where beekeeper was initialized	Set of town_patches	Cells	-----
num_loads	Number of loads owned by a beekeeper	1 - 15	Integer	Beekeeper data
my_loads	Identity of loads	*load_id* = *who* number of *beekeeper*	Integer	----
commercial?	Indicates whether beekeeper is commercial	True/False	Boolean	Beekeeper data
potential_targets	Agent-set of patches with forage availability in a time step for individual beekeepers	Set of patch coordinates	Cells	-----
my_target	Agent-set of patches chosen by individual beekeepers after applying decision criteria	Set of patch coordinates	Cells	-----
reftarget	One patch randomly selected from my_target as a reference to finalize optimum forage locations for each load (1 patch = 1 load)	Set of patch coordinates	Cells	-----
split_number	Indicates number of times beekeepers split their loads to find target cluster.	0 - 1	Integer	Only one split is included in this version of the model.
distance_this_tick	Euclidean distance travelled during current time step	0 – distance in a time step	Float	Run result for each time step
total_distance_travelled	Sum of Euclidean distance travelled in each time step	0 – sum distance travelled in all time step	Float	Run result

Shifting	Average number of times hives moved		Float	Run result
Load Agents				
load_id	Identifier for the owner beekeeper	0 – (beekeeper population – 1)	Integer	---
my_forage_cell	Patch for load to migrate in current time step selected according to load owner's decision	Set of patch coordinates	Cells	---
move_count	Counter for load movement	0 – max number of times moved	Integer	Run result
visited?	Indicates whether owner beekeeper has visited the load	True / False	Boolean	---
Forage availability environment cells				
Availability_months	List to store Boolean values of forage availability for 12 months	0 – 1	Boolean	Cell value of forage availability output rasters (zero = 0 and 1 – max value = 1)
available_forage	Indicate whether forage is available in current time step	0 – 1	Boolean	Value for current time step from availability list
jan feb mar apr may jun jul aug sep oct nov dec	Patch variables for each month to read monthly forage availability raster value for each scenario	0 – 9	Integer	Cell value of forage availability output raster for current month
sp_premium _months	List to store Boolean values of forage availability for 12 months	0 – 1	Boolean	Cell value of forage availability output rasters (zero = 0 and 1 – 2 = 1)
sp_premium	Indicate whether forage is available in current time step	0 – 1	Boolean	Value for current time step from *sp_premium* _months list
janP febP marP aprP mayP junP julP augP sepP octP novP decP	Patch variables for each month to read monthly availability of premium species for each scenario	0 – 2	Integer	Cell value of output raster representing the availability of premium species for current month

premium?	Decision variable - Indicate whether premium species is available in current time step –	True / False	Boolean	Premium species identified from stakeholder engagement based on reliability and high price product. Value updated based on *sp_premium* variable
sp_rich	List to store raster values of forage availability for 12 months	0 – 9	Integer	Cell value of forage availability output rasters for 12 months
richness	Raster value for current month	0 – 9	Integer	Value for current time step from sp_rich list
high_rich?	Decision variable – True if value for richness variable is greater than or equal to three	True / False	Boolean	Authors' assumption – Value updated based on richness variable
Harvest_count	A number of times a patch is used during simulation run	0 – max number of times a patch is used	Integer	Run result

* Variables created to improve execution speed of the model.

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APPENDIX 8 - PUBLICATION IN DATA IN BRIEF

Data in Brief 46 (2023) 108783

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Data in Brief

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Data Article

Data representing climate-induced changes in the spatial distribution of key bee forage species for southwest Western Australia

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ABSTRACT

The dataset includes (i) species occurrence points, and (ii) Species Distribution Model (SDM) outputs under current conditions and a moderate emission (RCP 6.0) climate scenario, for 30 key bee forage species in southwest Western Australia (WA). Occurrence data were obtained from open data sources and through stakeholder engagement processes. SDM outputs were predicted using the Maxent algorithm with the change in species range analysed using QGIS software. The model outputs provide insight into the potential implications of climate change on important bee forage species in southwest WA, including dominant melliferous tree and shrub species. Changes in these species are likely to have repercussions to the ecological and social systems where a facilitatory relationship exists. This dataset is important for informing conservation efforts within the southwest Australian biodiversity hotspot.

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Specifications Table

Subject	Ecological modeling
Specific subject area	Geography
Type of data	Table; Maps; Figure
How the data were acquired	Key bee forage species were identified through semi-structured interviews with WA commercial beekeepers [1], and from verified citizen science and WA herbarium records collated through the national open-source biodiversity data platform, the Atlas of Living Australia (ALA)[1]. These data were then used to identify species occurrence points and model spatial changes in species distribution for 30 melliferous species across southwest WA. Environmental data used in the SDM for current (1976 – 2005) and future (2055) time periods were bioclimatic variables prepared for Australia (sources listed in data accessibility section).
Data format	Filtered and analysed.
Description of data collection	The point locations of key forage species were identified through semi-structured interviews and participatory GIS mapping exercises conducted with 14 commercial beekeepers owning 50 or more beehives. Additional species occurrence data were collected from the ALA for 1950 to 2021.
Data source location	• Region: Southwest Western Australia • Between 26° to 35.15° South latitude and 113.15° to 126.6° East longitude
Data accessibility	All filtered and analysed data are available at Patel et al. [2]. Repository name: Mendeley Data Data identification number: 10.17632/9vnztvcrcp.3 Direct URL to data: https://data.mendeley.com/datasets/9vnztvcrcp/3 Other data sources: 1. Species occurrence data: https://spatial.ala.org.au [3] 2. Climate data: (i) Baseline scenario: http://www.bom.gov.au/jsp/awap/ [4] (ii) Future scenario: Vanderwal [5] Further information on the thematic methodology for the processed semi-structured interview data is available in Patel et al. [1].
Related research article	*V. Patel, E. M. Biggs, N. Pauli, and B. Boruff, Using a social-ecological system approach to enhance understanding of structural interconnectivities within the beekeeping industry for sustainable decision making, Ecology and Society. 2020 25(2):24.* https://doi.org/10.5751/ES-11639-250224.

Value of the Data

- The data present current and future occurrence maps for 30 species native to the southwest Australian biodiversity hotspot and provides estimates of potential shifts in distribution ranges based on a moderate emission (RCP 6.0) climate scenario.
- The data are beneficial to researchers examining the impact of climate change on the ecosystem service provision of melliferous flora in Western Australia.
- The data will inform conservation efforts within the southwest Australian biodiversity hotspot by providing an assessment of climate-induced change in the geographic distribution of key melliferous species.

[1] The Atlas of Living Australia (ALA) is an Australian node of the Global Biodiversity Information Facility (GBIF).

1. Objective

The research this publication supports [1], which describes the structural interconnectivities between bees, beekeeping, and forage landscapes, and explains how natural and anthropogenic pressures acting upon these landscapes will affect the beekeeping system of Western Australia (WA). The data presented here was generated to support an enhanced understanding of the impacts of climate change on bee forage found within the South West Australia Ecoregion (SWAE), Australia's only biodiversity hotspot. The 30 species included in this study represent the key forage species used for honey production in Western Australia. This data illustrates how key bee forage species distribution will change relative to a future climate scenario (Representative Concentration Pathway 6.0, Global Climate Model (GCM) CSIRO Mk3 - 2055), understanding how access to these species will change, and how such changes will alter beehive migration patterns across the state was the catalyst for this analysis and therefore defined the scope.

2. Data Description

The data provided here include (i) species occurrence points, (ii) current and future distribution range maps, and the magnitude and direction of shifts in distribution ranges, of 30 species targeted for honey production in Western Australia. The target species used in this study are listed in Table 1. Species occurrence data were compiled using records obtained through the Atlas of Living Australia (https://spatial.ala.org.au), cleaned by removing incomplete information or incorrect coordinates, and merged with occurrence records collected through participatory GIS mapping exercises conducted with individual commercial beekeepers.

Table 1
List of thirty species targeted for honey production by beekeepers in Western Australia.

Species Name	Common Name	Type
Banksia attenuata	Candle banksia/Yellow banksia/Slender banksia	Tree
Banksia menziesii	Firewood banksia/Red banksia/Menzies banksia	Shrub
Banksia sessilis	Parrot bush	Shrub
Banksia sphaerocarpa	Fox Banksia	Shrub
Calothamnus quadrifidus	One-sided bottlebrush	Shrub
Corymbia calophylla	Marri/Red gum/Port gregory gum	Tree
Eucalyptus accedens	Powderbark wandoo	Tree
Eucalyptus annulata	Open-fruited mallee	Tree
Eucalyptus burracoppinensis	Burracoppin mallee	Tree
Eucalyptus cornuta	Yate	Tree
Eucalyptus diversicolor	Karri	Tree
Eucalyptus dundasii	Dundas blackbutt	Tree
Eucalyptus flocktoniae	Merrit	Tree
Eucalyptus incrassata	Lerp mallee/Yellow mallee	Tree
Eucalyptus lesouefii	Goldfields blackbutt	Tree
Eucalyptus longicornis	Red morrel/Morrel	Tree
Eucalyptus loxophleba	York gum	Tree
Eucalyptus marginata	Jarrah	Tree
Eucalyptus melanoxylon	Black morrel	Tree
Eucalyptus occidentalis	Flat-topped yate/Swamp yate	Tree
Eucalyptus platypus	Moort	Tree
Eucalyptus ravida	Bronze & silver gimlet	Tree
Eucalyptus redunca	Black marlock/Mallee form of Wandoo	Tree
Eucalyptus salubris	Gimlet	Tree
Eucalyptus stricklandii	Strickland's gum	Tree
Eucalyptus transcontinentalis	Redwood	Tree
Eucalyptus wandoo	Wandoo/White gum	Tree
Hakea trifurcata	Two-leaf hakea/White bush/Kangaroo	Shrub
Leucopogon conostephioides	May flower/White bell	Shrub
Leucopogon_oldfieldii	Oldfields beard-heath	Shrub

SDM outputs were generated using MaxEnt. SDM performance was based on the Area Under the Curve (AUC) and True Skills Statistics (TSS). The AUC values approaching 1.0 for all model outputs indicated good predictive performance. Maximum training sensitivity plus specificity logistic thresholding was used to convert each species distribution model to a binary presence-absence grid. SDM outputs mapped for the 30 individual species are presented in Patel et al. [2][2], which indicate current species distribution and change in distribution relative to the moderate emission (RCP 6.0) climate scenario. The magnitude and direction of species distribution range shift is provided in Patel et al. [2] as Table 1.

3. Experimental Design, Materials and Methods

3.1. Identifying key forage species

To identify the forage species targeted by commercial apiarists, semi-structured interviews were conducted with 29 beekeepers (operating more than 50 hives). Human ethics approval was attained to undertake this research. The participants were selected under the guidance of the Bee Industry Council of Western Australia (BICWA), and the snowballing method. From the interview data[3], important bee forage species targeted by beekeepers were shortlisted (n = 30; Table 1) as the most mentioned species by the participants. The coordinates for each apiary permit owned by a participant beekeeper was collected from the WA state government Department of Biodiversity, Conservation and Attractions (DBCA). A Participatory Geographic Information System (PGIS) mapping approach was then used with each interviewee to identify specific target species for each apiary permit.

Additionally, species occurrence data for the 30 shortlisted species were extracted from the Atlas of Living Australia[4] (https://spatial.ala.org.au) spatial portal. Occurrence records were clipped using the study area boundary, prepared from spatial data for the Interim Biogeographic Regionalisation for Australia (IBRA) (https://www.environment.gov.au/). PGIS mapping data and ALA records were combined, providing comprehensive representation of species occurrence samples, as an aim to overcome spatial bias in ALA records [6,7]. GIS vector files (shapefiles) from ALA and PGIS data were merged in QGIS 3.10 to compile occurrence points for each species.

3.2. Species spatial extent

Modern SDM in Australia began with the development of the BIOCLIM package in 1984 [8], and continuously progressed to more complex machine learning algorithms including MaxEnt [9]. In this study, easy-to-use presence-only method Maxent was used to obtain the geographic distributions of key bee forage species due to its high prediction performance when compared to other known methods [10]. MaxEnt uses presence-only data and background (pseudo-random) points randomly distributed across the study extent to estimate the closest to uniform (maximum entropy) distribution for a range of independent environmental variables [11]. Species occurrence data were randomly allocated as 70% training and 30% test data for species distribution modelling in MaxEnt version 3.4.1. SDMs for each species were calculated using 10,000 pseudo-

[2] SDM outputs in Patel et al. [2] include baseline distribution, future distribution, change in distribution, and species range shift maps.

[3] Interview themes used in semi-structured interviews are available in related research article Patel et al. [1].

[4] Atlas of Living Australia (ALA) is a platform for providing open source biodiversity data covering over 85 million records of more than 111,000 species, aggregated from multiple sources and citizen science across Australia (ALA, 2020). Bias in ALA data has been recognised in the literature with recommendations for approaches such as additional sampling and digitising to overcome data quality gaps [7].

Table 2
List of 19 bioclimatic variables obtained to represent baseline and future scenarios [4,5,13]. The variables selected for use in species distribution modelling (SDM) using MaxEnt software are highlighted with bold letters.

Code	Variable
Bio1	Mean annual temperature
Bio2	Mean diurnal range
Bio3	**Isothermality**
Bio4	Temperature seasonality
Bio5	**Max temperature of warmest month**
Bio6	Min temperature of coldest month
Bio7	Temperature annual range
Bio8	Mean temperature of wettest quarter
Bio9	Mean temperature of driest quarter
Bio10	Mean temperature of warmest quarter
Bio11	**Mean temperature of coldest quarter**
Bio12	**Annual precipitation**
Bio13	Precipitation of wettest month
Bio14	Precipitation of driest month
Bio15	Precipitation seasonality
Bio16	**Precipitation of wettest quarter**
Bio17	**Precipitation of driest quarter**
Bio18	Precipitation of warmest quarter
Bio19	Precipitation of coldest quarter

random points and six bioclimate variables to obtain the logistic outputs for each species using a five-fold cross-validation. To increase model performance, only 'hinge features' were used [12].

3.3. Climate scenarios

Species distributions were obtained for two climate scenarios, baseline and future. The baseline scenario represents Bureau of Meteorology climate datasets (1976 – 2005) prepared for Australia and used for climate projects [4]. The future scenario uses data from the moderate emission Representative Concentration Pathway (RCP) 6.0 scenario for the Global Climate Model (GCM) CSIRO Mk3 for the year 2055, sourced from Vanderwal [5][5]. Total 19 bioclimate variables (Table 2) were obtained for each climate scenario.

To minimize multicollinearity, six of these predictors including, Isothermality (Bio3), Maximum temperature of the warmest month (Bio5), Mean temperature of coldest quarter (Bio11), Annual precipitation (Bio12), Precipitation of wettest quarter (Bio16) and Precipitation of driest quarter (Bio17) were selected for use in MaxEnt modelling (presented with bold in Table 2). The variable selection was based on the Pearson correlation coefficient ($r < 0.7$) and prior SDM studies involving the study species [14,15].

3.4. Assessing the change in species geographic distribution ranges

MaxEnt outputs were converted from ASCII to Tiff file format using open-source QGIS [16] for further analysis. To quantify the change in species range between the baseline and future scenario, change in area and the magnitude and direction of shift were calculated using the QGIS. A complete GIS workflow is provided in Fig. 1.

Both baseline and future outputs for each species were reprojected to WGS 84/UTM Zone 50 S to facilitate area level calculations. The raster cell size was set at 3000m $\times$ 3000 m. The cell

[5] The set of variables presented here is not generated using BIOCLIM. The dataset is a collection of bioclimatic variables provided as spatial layers downscaled to 0.05 degrees (~5km resolution).

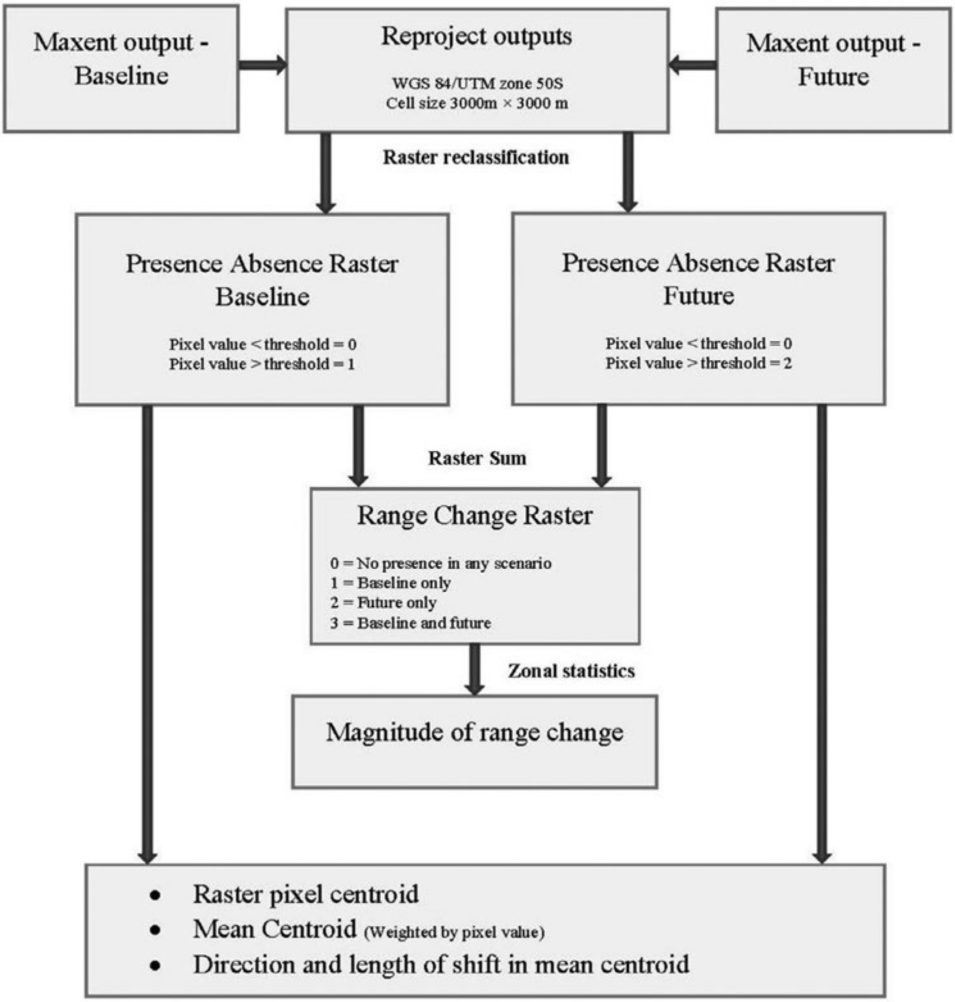

Fig. 1. Workflow highlighting steps for range change analysis using QGIS

size was selected to represent 3 km apiary separation regulation as discussed in [1]. Reprojected raster layers were then converted to a binary presence-absence raster using *maximum training sensitivity plus specificity* logistic threshold [14,15,17]. Using the threshold values (Table 1 in [2]), each species output was reclassified where pixel values less than the determined threshold were reclassed to 0, and pixel values greater than the threshold were reclassed to 1 (for baseline scenario) or 2 (for the future scenario). The spatial overlap between baseline and future scenarios for each species was calculated as the mathematical addition of the reclassified grids. The total number of presence pixels for each class including ‘baseline only’ (pixel value = 1), ‘future only’ (pixel value = 2), and ‘baseline and future’ (pixel value = 3) were then multiplied by the cell size (9 km^2) to calculate species distribution areas by class (Fig. 1).

The percentage change in the area of each species’ geographic range in the future was calculated as: [(RF/RB) - 1] *100. Where RF represents the distribution area in the future (sum of the area of pixel values 2 and 3) and RB is the distribution area at baseline (sum of the area of pixel values 1 and 3). To assess the shift in distributions, the mean center (latitude and longitude) of presence cells for each species was calculated for the baseline and future scenarios. The distance and compass directional shift between mean centers for each scenario was then calculated and together, the two metrics provided an indication of the magnitude and direction of changes to each species distribution following climate change.

Ethics Statements

This work involved human subjects for data collection. We confirm that the relevant informed consent was obtained from the participants and the research was carried out upon the University of Western Australia human ethics approval (RA/4/1/9247).

CRediT Author Statement

Vidushi Patel: Conceptualization, Methodology, Programming, Formal analysis, Data curation, Writing – original draft preparation; **Bryan Boruff:** Conceptualization, Methodology, Writing – review & Editing, Resources, Supervision, Funding acquisition; **Eloise Biggs:** Writing – review & editing, Visualization, Supervision; **Natasha Pauli:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Climate induced change in spatial distribution of bee forage species in Southwest Western Australia (Original data) (Mendeley Data).

Acknowledgments

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