

Perspective

A New Approach to Inform Restoration and Management Decisions for Sustainable Apiculture

Joanne Lee Picknoll ^{1,2,*} , Pieter Poot ^{1,2}  and Michael Renton ^{1,2,3}

¹ School of Biological Sciences, The University of Western Australia, 35 Stirling Hwy, Crawley, Perth, WA 6009, Australia; pieter.poot@uwa.edu.au (P.P.); michael.renton@uwa.edu.au (M.R.)

² Cooperative Research Centre for Honey Bee Products, 128 Yanchep Beach Rd, Yanchep, WA 6035, Australia

³ School of Agriculture and Environment, The University of Western Australia, 35 Stirling Hwy, Crawley, Perth, WA 6009, Australia

* Correspondence: joanne.picknoll@research.uwa.edu.au

Abstract: Habitat loss has reduced the available resources for apiarists and is a key driver of poor colony health, colony loss, and reduced honey yields. The biggest challenge for apiarists in the future will be meeting increasing demands for pollination services, honey, and other bee products with limited resources. Targeted landscape restoration focusing on high-value or high-yielding forage could ensure adequate floral resources are available to sustain the growing industry. Tools are currently needed to evaluate the likely productivity of potential sites for restoration and inform decisions about plant selections and arrangements and hive stocking rates, movements, and placements. We propose a new approach for designing sites for apiculture, centred on a model of honey production that predicts how changes to plant and hive decisions affect the resource supply, potential for bees to collect resources, consumption of resources by the colonies, and subsequently, amount of honey that may be produced. The proposed model is discussed with reference to existing models, and data input requirements are discussed with reference to an Australian case study area. We conclude that no existing model exactly meets the requirements of our proposed approach, but components of several existing models could be combined to achieve these needs.

Keywords: *Apis mellifera*; bee; honey production; landscape design; restoration; model



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1. Introduction: What Is the Problem We Are Trying to Solve?

The global honey industry has a current gross value of production (GVP) of more than US\$7.3 billion per annum, with the largest producers being China, Turkey, and Ukraine [1]. Australia is also a significant producer (within the top 20%) and, with about 1800 commercial apiarists [2], produces an average of 13 kilotons of honey per annum [1]. However, the sustainability of the Australian and global apicultural industries continues to be questioned [3–7]. This includes the industry's ability to meet growing demands for pollination services [8], honey, and other bee products in the future [9]. Currently, global stocks of managed honey bees are growing too slowly (~45% increase) to match the rapid growth (300% increase) in the fraction of agriculture dependent on pollination by animals [8], and a shortage of managed honey bees has been reported for a number of countries [10]. Of additional concern are well-publicised accounts of elevated losses of managed honey bees in many regions [11,12], including long-term declines in North America and Europe [13–15]. Among multiple causes [16–18], land-use change and the subsequent loss and fragmentation of natural habitats are the most frequently cited stressors linked to the global declines [16,19,20]. Land-use change significantly reduces the amount and diversity of floral resources (e.g., nectar and pollen) available to the honey and pollination industries [21]. Since floral resources are a major regulator of bee populations [22–24], it is not surprising that beekeepers frequently cite poor foraging conditions and starvation as the cause of colony losses [14,25,26].

Land-use change and the associated loss of floral resources also lead to reduced hive yields for apiarists [24,27,28]. This occurs when the nectar supply is insufficient to meet the colonies' demands for feeding workers and producing surplus honey. It also occurs when the pollen supply is insufficient to support the level of brood production and colony expansion necessary for optimal honey production [4,29,30]. When resources are particularly scarce, the amount of energy spent searching for and collecting forage (energy cost) exceeds the energy gain [31], and colonies reduce foraging [32,33] and deplete stores within the hive [31,32,34,35].

Resource limitations may also cause apiarists to overstock existing forage with hives (beyond the carrying capacity of the flora) and this can lead to intense resource competition at the site among apiarists, managed colonies [36,37], and native flower visitors [38], and further reductions in hive yields [36,37]. It can also have serious financial implications for the apiarist [36] and eventually lead to withdrawal from the industry [39,40]. Records from the last 56 years show honey yields have declined in many regions, including Australia, which is one of the few countries to remain free of *Varroa destructor* [1,41], perhaps indicating that the capacity of existing resources to sustain the growing honey bee product and pollination industries has already been exceeded.

Habitat conservation, together with targeted landscape and habitat enhancement, have a fundamental role in ensuring adequate floral resources are available to sustain the growing honey bee industries [4,6,7,42–44] and deliver secondary ecological, aesthetic, and economic benefits [45]. So far, the focus has been on restoring plant-pollinator community structure and function within the pollination industry (e.g., [46–52]). With the exception of a few field trials on a narrow range of flowering plants [53–57], there has been limited concerted research effort towards restoring landscapes for honey production. In addition, few studies have attempted to quantify the value of floral resources or sites for bees (but see e.g., [21,58–64]), or predict their value for honey production [65,66]. Consequently, methods to help inform the restoration of landscapes for commercial honey operations are currently limited, and there is an urgent need to develop science-based methods to test and guide landscape designs before further financial investments are made. In particular, methods are needed to inform decisions about what to plant, how large to make the plantings, and how to distribute the plantings across the landscape [6,67–71]. Methods to inform decisions about optimal stocking rates, movements, and placements for hives [68,72,73] are also needed. This paper addresses these issues by proposing a modelling approach that will integrate available information and simulate key processes in order to evaluate potential site productivity; design plantings to optimise honey productivity; predict how changes to hive numbers, movements, and placement affect productivity; and identifies key knowledge and data gaps to prioritise in future research.

2. Overview: What Is Our Proposed Solution?

Our approach is centred on a model that integrates the decision variables and data inputs to predict honey yields and profit over time (Figure 1). The decision variables are the plant species mix, area and spatial arrangement, and the hive stocking density, movement, and spatial arrangement. The model accounts for how changes to each decision variable affect the bee population, supply of resources, demand for resources, foraging, amount of resources collected, amount of resources consumed, and hence the honey and pollen stores and surplus honey produced. Data inputs on the flowering phenology, nectar production, and pollen production of new plants (plants being considered for restoration) and existing plants (plants already growing on the site), allow the model to account for the production potential of different species, and thus helps the user to design plantings that synchronise the resource supply with the colonies' temporally changing demands. Data inputs on the climate, landscape configuration (area, density, and location of existing resources), and resource competition (with other flower visitors) allow the model to account for differences in environmental and climatic conditions between sites and over time. Finally, economic data allows the model to account for differences in the economic value of honey from

different floral sources and differences in the costs of planting different species, as well as costs of moving hives. Optimisation algorithms can then be used to identify optimal decisions (e.g., the best choices and designs for plantings or the best stocking densities, locations, and movements for hives), under the constraints of any particular needs of the business (e.g., a desire to restore the site predominantly with local native species). We now discuss the various requirements of the proposed approach, addressing each component of the conceptual framework (decision variables, prediction model, data inputs, and optimisation) in turn.

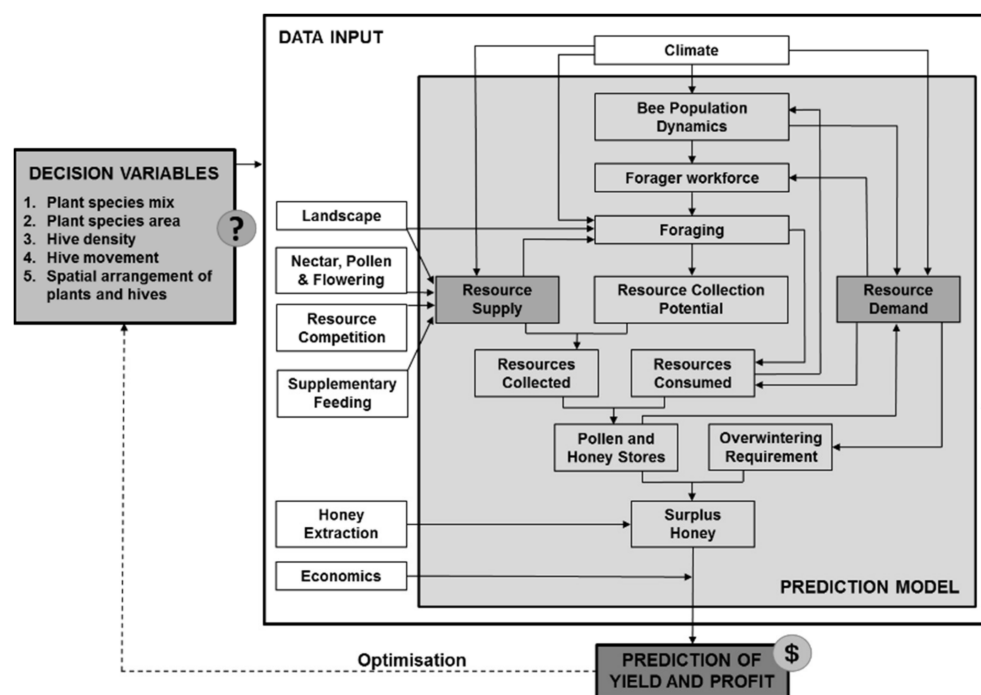


Figure 1. Conceptual framework for our proposed approach to use a simulation model that integrates available data to predict honey production, in order to optimise the choice of plants, area of plants, density of hives, movement of hives, and spatial arrangement of plants and hives on restored or natural sites.

3. Decision Variables: What Kind of Decisions Will This Approach Help with and Why Are They Important?

3.1. Plant Species Mix

Since honey bees utilise resources from a large range of plants (>40,000 species are thought to be of some importance to bees; [74]), each with different flowering times and offering different resources (nectar, pollen, or both), selecting a suitable plant species mix can be challenging [52].

Nectar (which is converted into honey) is important to the colony because it provides their main source of carbohydrates (energy), needed to fuel daily activities, such as thermoregulation, wax production, and flight [20]. The value of nectar plants for apiculture varies considerably [75], but is determined, for the most part, by their potential for honey production (melliferous potential). This depends on the total number of flowers the plant produces, the amount of nectar-sugar secreted by each flower (determined by the volume and concentration of the nectar), and the plants' length and regularity of flowering [62]. Plants with a very high melliferous potential (>500 kg/ha/season; [76]) are particularly valuable. However, the plant's value also depends on the marketability and properties of the honey produced, including its colour, flavour, aroma, density, viscosity, granulation, and bioactivity. Kinds of honey with desired or marketable qualities, such as antibacterial properties, are likely to attain a high market price for the apiarist. If high-value plants also have a high melliferous potential, the economic outcomes will be considerably improved.

Pollen plants are equally important to apiculture [75] and provide the colonies' main source of protein, lipid, vitamin, and mineral intake, necessary for feeding and rearing brood [20,77,78]. These nutrients are also required to grow and repair body tissues [79], build fat cells [80], increase immunity [81] and disease resistance [82,83], and longevity of the colony [84,85]. The value of pollen-producing plants for apiculture varies considerably, due to large differences in the amount of pollen produced [60,86–89], and the chemical composition and nutritive benefit of the pollen [90–94]. The crude protein content of the pollen is particularly important and ranges from 2% to 60% for insect-pollinated plants [91]. However, optimal levels required for brood rearing range from 23% to 34% [95,96]. Colonies consuming pollen within this range produce significantly more brood [95,97] and superior workers [96,98,99], have improved rates of survival and longevity [100] and a greater potential for collecting resources and producing honey [24,29,30,97,101,102]. However, there is some evidence that high crude protein levels (>38%) in artificial diets are deleterious to colonies [79,95,96,103,104]. Although not proven for natural diets, the effect requires further investigation (but see e.g., [105]).

The balance of essential amino acids is also an important indicator of pollen's nutritive value. Ten essential amino acids are required in different minimum quantities for colony growth and development [79]. Unfortunately, the pollen produced by many flowering plants are deficient in one or more essential amino acids [106–108]. Consequently, colonies kept on limited pollen sources may be susceptible to disease (particularly fungal infection by *Nosema*), produce little or no brood, and may completely perish [83,109,110]. The non-protein component of pollen (e.g., lipids, vitamins, and minerals) is also considered important, but its role is not well understood (reviewed by [20,43,78,111–113]). To reduce the risk of any of the above-mentioned nutritional deficiencies, planting a mixture of flowering plant species has been suggested [43,81]. Provisional guidelines suggest a minimum of twelve plant species (three to five blooming simultaneously) may be sufficient to maintain populous colonies [70,114,115]. However, because pollen can be deficient in one or more nutrients, it will be important to target nutritionally balanced species combinations [93]. Plant selections would also need to complement the phenology of existing plants and bridge any gaps in flowering or resource provisioning at the site [49] and ideally account for pollinator preferences. Nectar quality plays a significant role in pollinator preferences, with nectar-sugar (sucrose) concentrations between the range of 30% to 50% being more attractive to bees and offering greater calorific rewards [102,116–118]. However, at greater concentrations (above 60%), nectars become too viscous for rapid withdrawal and are rarely collected by bees [118–120]. Preferences for pollen (reviewed by [121]) are not well understood but are commonly driven by the availability [122–124] and concentration of viable pollen [125–127], and duration of flowering [123,124]. Finally, attractants (e.g., caryophyllene), deterrents, and toxins (e.g., caffeine and nicotine) in the nectar and pollen may also play a role in pollinator choices [90,128,129], depending on their concentration [130].

3.2. Plant Species Area and Hive Density

Decisions about the planted area of different species and hive stocking rate should account for the colonies' seasonally changing demand for resources (whilst hives remain on-site). If decisions also account for existing resources already growing on-site, the restoration work will be more easily managed and cost-effective [131] and plantings can be more effectively targeted towards balancing the resource supply with the colonies' seasonally changing demands [61]. Colonies regulate their demand for carbohydrates (nectar) and protein (pollen) as larval numbers increase [132–134] and pollen and honey stores within the hive diminish [133,135,136]. During winter, when there is little or no brood, there will be a strong carbohydrate bias for resources needed to feed the adults [131,137]. However, when the queen begins laying eggs there will be a shift towards protein to feed growing numbers of brood [136,137]. Therefore, resource requirements will depend on colony dynamics and the number and size of colonies, which can vary between 10,000 bees in

late winter and 70,000 bees at the population peak in late spring [138,139]. If the resource supply is limiting for a period of time, because the flowering plant species area is too small and/or the hive density is too high, then the carrying capacity of the site will be exceeded. There will be insufficient provisions to feed existing hive members, to produce new brood or make honey, and larvae may be cannibalised [140]. This can be corrected by increasing the amount of resources, providing a sugar or pollen supplement, or reducing the number of hives at the site. Alternatively, if the resources are in oversupply, there will be insufficient bees to collect all of the forage and additional hives may be added to increase production. Eventually, increases in the number of hives or the amount of resources will be constrained by the size of the apiary (capacity of the business) and the area available for planting.

3.3. *Hive Movement and Spatial Arrangement of Plants and Hives*

Decisions about hive movements and the spatial arrangement of the plants and hives would need to account for the capability of foragers to utilise and navigate the landscape [49,141]. Plant and hive arrangements determine how accessible the resources are to the colony, the probability that they will be discovered or collected [73,102,142], and the rate of energy return during foraging [143–146]. Placing smaller numbers of colonies more frequently across the landscape is likely to reduce travelling time to collect forage and competition between bees and increase the rate of resource collection and honey production [36,73]. The optimum number and placement of hives are likely to depend on the same factors that determine a colonies' maximum flight range. These include the mix, quantity, and quality of the resources within the landscape, competition for resources (with other colonies or flower visitors), and the mortality risk during flight [33,42,147]. Optimum hive placements and numbers are likely to change temporally and be determined by the balance between the supply and demand for resources [142,148,149] and climatic conditions outside the hive. In winter, when bees' resource demands are smaller (there are fewer bees to feed), resources close to the hive may be sufficient to meet colony demands. In addition, resources planted far from the hive may not be collected because less favourable climatic conditions allow short flights only [32,34,61,150].

The composition and configuration of the plants also affect the way resources are utilised. Because foragers commonly visit a single flowering species per flight [142,151], block plantings (clusters) of flowering plants are recommended over widely scattered plantings [115,152]. Block plantings are more attractive to and easily discovered by foragers and improve foraging efficiency [153–155]. Interactions between co-flowering plants (neighbouring plants that flower simultaneously) may also require consideration. Co-flowering plants support and share pollinators, though can interact in a positive (facilitative), negative (competitive), or neutral way [156]. For example, eucalypts are thought to have a competitive effect on the attraction of pollinators to co-flowering *Leptospermum* species [157]. Plant-pollinator interactions are not well understood and difficult to predict because they depend on many factors, including the density and abundance of the plants and pollinators [156,158], and require further investigation.

Hive migration may also influence planting decisions and when apiarists are unable to move their hives (around the site or between sites), it will be important to offer a greater diversity of plants within the foraging range of the colonies (e.g., plants that flower in each season). This would ensure the colonies' resource and nutritional demands are met whilst the hives remain at fixed locations (which may be year-round). Keeping hives stationary on a site could reduce foraging efficiency and hive productivity, but also reduce costs and biosecurity risks; understanding these trade-offs would allow apiarists to make informed decisions about hive movements.

4. The Model: What Do We Need the Model to Do?

At the centre of our proposed approach is a model that predicts honey production based on the decision variables and input data. To predict the amount of surplus honey that may be produced by an apicultural operation, the model needs to first predict how the

following five variables change over time: (1) the resource supply available for producing honey (e.g., nectar and pollen), (2) the potential for bees to collect resources, (3) the amount of resources collected, (4) the bees' demand for resources, and (5) the consumption and storage of resources. These predictions will in turn depend on the different input decision variables and input data (Figure 1).

The resource supply at a given time is determined by the mix of nectar and pollen plants flowering in the landscape. Nectar would be the most important resource for the model to consider, as honey is produced from nectar. At a minimum, the model would need to account for the quantity and timing (flowering) of nectar-sugar production for all significant nectar-producing plant species on the site (i.e., both existing and new species being considered for planting), along with the area and density of each species (landscape factors). Ideally, the model may also account for inter-annual variation in nectar production and exploitation of this resource by other competitors. Pollen is another important resource since limitations in pollen negatively affect the population and dynamics of the hive. A simple model might assume that pollen was non-limiting, but ideally, the model might also account for the quantity or even the quality of this resource (e.g., crude protein and amino acid content of the pollen). Possible supplementary feeding could also be accounted for in resource supply.

The colonies' potential to collect nectar or pollen depends on the size of the foraging workforce and the number of foragers allocated to collect each resource (nectar or pollen), which can be predicted using a model of beehive population dynamics. Ideally, the population component of the model would account for the egg-laying rate of the queen and the longevity and mortality rate of each life stage (egg, larvae, pupa, hive-bee, and foraging bee) in the colony. Since the egg-laying rate of the queen likely depends on seasonal and regional conditions, space or resource limitation in the hive, and the number of adults available for brood care, it would also be important to account for these. The colonies' potential to collect nectar or pollen is also strongly influenced by climate (which dictates the maximum daily foraging hours) and the spatial arrangement of the resources in the landscape. To account for spatial factors, a simple version of the model would define all of the plants within a foraging range as accessible, with plants further away from the hive having a reduced probability of collection, modelled using an appropriate dispersal kernel (e.g., [159]). However, a more sophisticated model might also predict the colonies' utilisation of resources using net energetic efficiency (which is dependent on the quality and distance of the resource), as the primary factor driving patch selection and the amount of time spent foraging. In a simple version of the model, where pollen availability is assumed to be non-limiting, the number of foragers available to collect nectar could just be reduced by the number required to collect the colony's pollen requirements.

The amount of resources collected will depend on the balance between resource supply and foraging. If the supply is limiting, foragers will only collect what is available and will not reach their full collection potential. Conversely, if the foraging workforce is limiting, foragers will be unable to collect all of the available resources. Therefore, whichever of the two factors is limiting will determine the amount of resources collected.

The bees' demand for resources will largely depend on the size and composition of the population, and the amount of resources required to feed colony members of each life stage. A simple version of the model might assume that the amount of resources required by foragers is constant, but a more sophisticated model might account for their energetic requirements, which will, in turn, depend on the distance and spatial arrangements of the floral resources at any time.

The amount of resources consumed and stored will then depend on the balance between the bees' demand for resources and the amount of resources collected. If the amount of nectar collected is greater than the demand for nectar, then the surplus nectar will be assumed to be converted to stored honey. If the amount of nectar collected is less than the demand for nectar, then stored honey will be reduced to supply energetic requirements. If stored honey is unavailable, then we could either assume supplementary

feeding is introduced, or that mortality rates would be increased and/or egg-laying rates reduced. If the pollen production of significant forage species on the site was also accounted for (pollen availability was not assumed to be non-limiting), then pollen deficits would similarly result in increased mortality or reduced egg production.

The units for the variables would need to be considered carefully, in order to account for conversion between them. We suggest that nectar, honey, and possibly energetic requirements could all be accounted for in equivalent grams of honey, while pollen and protein requirements (if included) could be accounted for in equivalent grams of protein.

Finally, we may want the model to account for economic factors. These may include differences in the expected market value of the honey produced from different floral sources; differences in the costs of planting and establishing different floral resources, and/or the costs of moving hives within or across sites.

5. Existing Models: Do Existing Models Already Do What We Need This Model to Do?

An extensive literature review found only three models [65,66,160] that are able to predict the production of an apiary using landscape variables. Each of these was distinctly different in its approach to predicting honey production and provide key insights for the development of our new approach.

The first model by Janssens et al. [65] used a simple approach to predict apiary production in the south of Belgium during the honey season (May to July). The authors considered all of the plants within a foraging range of 2 km from the apiary as accessible to bees. Forage plants within this range were surveyed and mapped using GIS software to provide information about the plants' location, density, and area. Data was also collected on the plants' flowering period and nectar productivity (from literature). The production potential of each species was calculated from the input data and summed to give an estimate of the total production for the apiary. Several limits were imposed on production and a rudimentary attractivity equation was applied to account for the effect of distance and patch quality on forager recruitment. The equation assumes a linear decay in production with increasing distance from the patch (as bees diffuse out from the hive) and greater attraction to high-quality patches (defined by the melliferous potential and density of the plants). However, the authors found that the model overestimated hive yields by more than 100 times the observed values. This was attributed to the model not adequately accounting for foraging limitations and the difficulty in predicting production for sites with a range of floral diversities. The authors acknowledged that their model did not account for the diurnal pattern of nectar secretion by each species, time costs of foraging (from the apiary and between patches), pollinator preferences, or the effects of climate. Model outputs would be significantly improved by including seasonal effects, as well as a colony component. This would allow the model to account for temporal variations in the size and dynamics of the colonies and their potential to collect and store resources. It would also allow the model to determine colony resource demands and account for the amount of resources consumed by colonies.

The second model by Albayrak et al. [66], uses fuzzy cognitive maps to account for a large range of factors affecting the production of apiaries in various provinces in Turkey. Factors accounted for included nectar-producing plants, pollen-producing plants, adult worker population, brood population, age of the queen, race of the bees, beekeeper experience, hive type, and a range of climatic variables. However, the output of this model was limited to a simple ranking of production as low (0–10 kg), medium (10–20 kg), or high (above 20 kg per hive). Also, the model and information interface do not allow the user to explore the effect of changing the decision variables (e.g., species mix, area of plants, number of hives) on honey production. Furthermore, model outputs are specific to provinces in Turkey and the information system is unable to be used outside its country of origin.

The third model (BEEHAVE) was developed by Becher et al. [160] for exploring the effect of different stressors on the performance of a single colony of honey bees and includes

honey and pollen stores as one of its outputs. It is significantly more complex than the other two models and is the first to link a colony model with a spatially explicit foraging model [161]. The colony model builds on existing models (e.g., [162,163]) and accounts for the development of each age class of the colony (eggs, larvae, pupae, and adults) for both workers and drones. The dynamics of the cohort are driven by the egg-laying rate of the queen, which depends on seasonal effects, the age of the queen, available space for brood, and the number of nurse bees in the colony. Each age class is assigned a mortality rate, but their survival is also dependent on there being sufficient workers for thermoregulation and brood care and sufficient resources (pollen) to feed the brood. The amount of resources consumed by the colony is determined by task-specific nectar and pollen consumption rates and includes energy requirements during flight. Although the colony model performs well in simulating beehive population dynamics (predictions of population dynamics fit empirical field data), it does not allow exploration with multiple interacting colonies because it accounts for the performance of single colonies only [161,164]. The BEEHAVE agent-based foraging model builds on a model of foraging behaviour by Sumpter and Pratt [165] to simulate foraging activities in a user-defined landscape. The landscape is defined by either manually entering landscape data, importing a landscape picture or through an optional external landscape model called BEESCOUT [166]. Landscape combinations are limited to four food sources (i.e., four patch types, with one representative plant in each patch) and surface water [161]. Landscape information (e.g., patch area and location) together with resource input data, determine the amount of resources available to the colony (nectar and pollen), the probability resources will be detected by scouts, and the utilization of resources by the colony. Forager preferences for nectar depend on the energetic efficiency of the patch, which is defined by the energy gain and energy cost of foraging in the patch. Forager preferences for pollen depend on the duration of the foraging trip. Foraging is limited by the number of hours available for foraging, which depends on the daily temperature and hours of sunshine. Although the foraging model accounts for a large range of factors, because landscape combinations are limited, it lacks versatility and is restricted in its representation of real sites [161]. Unfortunately, this makes the model unsuitable for predicting the availability of nectar and pollen in complex, heterogeneous landscapes.

We conclude that no one existing model adequately fills the requirements of our proposed approach and suggest that a new model that builds on the strengths of existing models is required. The aspects of nectar and pollen availability in the landscape should build on Janssens et al. [65], as well as the more recent work of Lonsdorf et al. [58], Baude et al. [21], Hicks et al. [60], Ausseil et al. [61] and Timberlake et al. [167]. The aspects of population dynamics, resource demands and consumption, and foraging should incorporate the strengths of BEEHAVE [160], as well as other colony (e.g., [168–175]) and foraging models (e.g., [58,147,176–179]).

6. Input Data: What Data Will We Need and How Can We Get It?

6.1. The Swan Coastal Plain Case Study Area: What Is It and Why Is It Relevant?

To illustrate our proposed approach, we use the Swan Coastal Plain (SCP) in the South-West of Western Australia as a case study. The SCP experiences a Mediterranean climate characterised by cool, wet winters and hot, dry summers. The vegetation of this biogeographical region is diverse (more than 8000 native species; [180]), largely endemic (47%), and dominated by Myrtaceae, Proteaceae, Papilionaceae, Mimosaceae, and Epacridaceae families [180,181]. Migratory beekeepers depend on the eucalypt forests, eucalypt woodlands, and mixed shrublands (kwongan) common to the region, for building their bee numbers in spring as well as producing honey. In fact, the species-rich eucalypts (together with closely related *Corymbia* species) make up the bulk (typically 80%) of the honey production [182–184], but apiarists in this region also rely on other native species (including *Agonis*, *Banksia*, *Callistemon*, *Calothamnus*, *Clematis*, *Daviesia*, *Grevillea*, *Hakea*, *Leptospermum*, *Leucopogon* and *Melaleuca*) and exotic flowering plants for nectar and pollen

(e.g., *Raphanus raphanistrum*, *Arctotheca calendula*, and *Echium plantagineum*). However, anthropogenic changes, including land clearing for agriculture, urbanisation, and industry, have greatly reduced the availability of these resources [39,123,185]. On the SCP, between 61% and 65% of the natural vegetation has been lost since European settlement [186,187]. This includes significant areas of eucalypt forests, coastal heaths, and banksia woodlands, previously utilised by apiarists [185]. Furthermore, remaining resources have been impacted by drought, fire, dieback, salinity, and flooding [2,39,185,188–190]. These impacts have created a limited resource base for apiarists, which is a significant bottleneck for the industry and will likely constrain performance and expansion into the future [123,189]. Whilst research and development efforts within the industry have led to advancements in product development (e.g., active kinds of honey) and improvements in beekeeper practices [190], the growing popularity of beekeeping (DPIRD beekeeper registrations) is increasing resource pressures. This has led to the creation of “bee farms” in different parts of the South-West that have been planted with high-value honey-producing plants (e.g., *Leptospermum* and *Eucalyptus* species). Furthermore, recent fires within and outside the study area have led to the development of bushfire recovery plans that include actions for restoring sites with important nectar and pollen plants for honey bees [2]. The move towards plantings for honey production and the diversity in potential floral resources makes the SCP an ideal case for discussing data requirements for our general method.

6.2. Landscape Data

The model will need data on the area cover for any major nectar or pollen resource plant species already growing on the site, ideally with their location and density. If not already available, this data may be obtained by mapping the site using ground-based surveys, aerial image interpretations, or a combination of these [191–193]. Aerial images and maps showing existing land uses, topography, vegetation, roads, watercourses, and soil types would also assist with site designs and restoration activities [194]. These features limit the available space and influence planting decisions in a number of ways (Section 8). In particular, land uses (including historic land uses) can alter the abiotic and biotic properties of the soil, affecting which species could potentially be established on the site [195]. For example, planted species may need to be tolerant of local conditions including waterlogging, salinization, and agricultural run-off. Planting decisions should also take into account how future climate change may affect plant species persistence and could include the use of provenances from nearby drier climates (i.e., climate-adjusted provenancing; [196]). Allowing for environmental change will broaden the evolutionary flexibility of plantings [196,197]. Aerial imagery for the SCP is readily available from Landgate (<https://www0.landgate.wa.gov.au/maps-and-imagery/imagery/aerial-photography/aerial> (accessed on 6 August 2020)).

6.3. Nectar, Pollen, and Flowering Data

Information about the resource characteristics of the plants already growing on the site, or being considered for planting will also be required, including the melliferous potential (kg honey/ha/season) and the timing, duration, and quantity of flowering (proportion of available buds in bloom/fortnight) of each species. This information could then be used to produce an input file with the quantity of honey that might be produced by each flowering species for each fortnight of the year (kg honey/ha/fortnight). A similar input file could be constructed for pollen production. Where available, information on the minimum, maximum and mean melliferous potential and pollen production of each plant would enable the model to account for intra-species variation. Data on inter-annual variation (e.g., [198]) in flowering would enable the model to account for plants that take longer to reach flowering maturity or plants that produce unreliable or infrequent crops of honey. Data on diurnal patterns of nectar secretion and pollen release would enable the model to address shortages in the nectar or pollen supply during the day. If the model was also

going to account for the quality of the pollen (e.g., crude protein and amino acid content of the pollen), this would also be required data for the model.

Unfortunately, the availability of nectar, pollen, and flowering data is a significant challenge worldwide. To date, most research efforts have been directed towards plants of economic significance in European countries [199,200]. An examination of the literature on melliferous plants of the SCP (and Australia more generally) shows these resources are less well researched and documented (Supplementary Data, Supplementary Appendix SA). A number of strategies could be used to overcome data limitations including: (1) calculating the melliferous potential and pollen production of each species using data sourced from available literature (for calculations and data requirements see Traynor [201] and Ion et al. [62]), (2) studying plants in the field or greenhouse to obtain missing required data (e.g., [21,60,62,86,88,91,92,120,123,202–205]), (3) using prediction models to estimate missing data (e.g., [21,60]), (4) estimating missing data using available data for related species (e.g., [21]), or species displaying similar morphology or plant traits, (5) estimating missing data using other types of data (i.e., beekeeper records of site or specimen honey yields), or (6) consulting an experts' opinion [61,66,206]. With more research, model outputs will continue to be improved as the quality and availability of nectar, pollen, and flowering data increases and better accounts for local growing conditions.

6.4. Resource Competition Data

The model would require data or estimates of the exploitation of resources by other flower visitors at the site (utilising the same resources as honey bees) if this was to be accounted for. A constant (as adopted by [179]), or temporally changing value, that accounts for the type, size [207], and/or abundance of other flower visitors could be used to estimate how much nectar (and pollen) is removed and thus not available to honey bees. On the SCP (and Australia more generally) honeyeaters (Meliphagidae) and other birds are the most abundant and widespread nectivores [208]. Typical honeyeaters (weighing 20 g) may require between 4 (non-breeding birds) and 15 (breeding birds) g sugar per day [209].

6.5. Climate Data

The effect of intra-annual climate variation can be accounted for by: (1) directly providing fortnightly demographic data (i.e., egg-production and life stage mortality and longevity) and foraging data (i.e., forager resource collection rate) that already accounts for varying seasonal or regional conditions, or (2) developing models that estimate fortnightly demographic and foraging parameters from imported localised weather data. Important weather data would include the daily air temperature, sunlight hours, wind speed, and rainfall [66,160,161]. On the SCP, high temperatures during much of the year allow an extended season for brood rearing, foraging, and honey production, and weather data may be readily sourced from the Australian Bureau of Meteorology.

6.6. Economic Data

The market value of the honey would be important input data for the model, especially if honey of different plant species have different values. Australian farmgate honey prices currently range from \$3.70 (e.g., red ash, crow ash, and white mangrove) to \$7.20 (e.g., certified organic honey) per kg (M. Bellman, personal communication, 2020). Retail prices may be as much as \$50 per kg for bioactive kinds of honey (S. McLinden, personal communication, 2018). Because the market value of honey fluctuates depending on product availability and demand, it will be important to source current data but also account for variation and uncertainty in future prices. Data for the SCP is sourced from honey price schedules available from local honey producers or retail businesses. Planting and maintenance costs may also be accounted for. These include the cost of seeds and seedlings, which may be obtained from supplier price lists. Other planting and maintenance costs may be obtained from local agronomists and restoration ecologists. Finally, operational costs (e.g., costs of moving hives), may also be important, and sourced from the apiarist.

6.7. Other Data

Input data accounting for beekeeper management (sourced from the apiarist) may also be desirable and include the maximum storage capacity of the hives, timing and quantity of supplementary feeds, and amount of honey extracted.

7. Optimisation: How Do We Determine the Best Design or Decision?

Finally, we propose that optimisation methods could be used to determine which decisions would produce an optimal outcome. Optimisation methods seek to maximise or minimise an objective function by systematically searching through input values subject to certain constraints [210]. In this approach, our objective might be honey production or annual profit; our input values might be the proportion of a site planted to each of a fixed number of potential plant species, the number of hives employed, and/or the location of hives within a site; and the function linking inputs to objective is the model itself. The constraints might be mathematical (e.g., the total of the proportions of planted area for each species cannot exceed one); environmental (e.g., only some parts of the landscape may be suitable for a given plant species, and so the proportion planted to that species cannot exceed that proportion of the landscape); or due to business values (e.g., no more than 10% of the landscape can be planted with non-local species). Given the relatively complex nature of the model linking inputs to objective, we expect that computational heuristic optimisation algorithms, such as evolutionary algorithms or simulated annealing, are likely to be more useful than purely mathematical techniques [211–214]. Such algorithms are not guaranteed to always find the absolute optimal solution, but rather a selection of near-optimal solutions [211]; this would be fine for our purposes, given the uncertainties in the underlying model and input data [215]. Multi-objective Pareto optimisation could also be considered e.g., generating a range of solutions that aim to maximise both honey production and the proportion of local species in a planting, while exploring the trade-off between the two [216].

8. Additional Considerations: What Else Do We Need to Consider?

A range of public, private, or industrial lands may be restored with honey plants to provide additional resources and income for apiarists and landowners. These include reclaimed mine sites [217], mixed-use farms [56,194,218], pollination reserves [69,219], burnt or degraded bushland [2], multiple-use reserves [53,57], desert dry zones [55], roadside reserves [57,220] and forestry plantations [40,221]. The economic, environmental, spiritual, and cultural objectives for each site are likely to be markedly different and need to be considered in the planting design and whole site plan [218,222]. The design also needs to function within the existing spatial landscape, which may already include multiple land cover types associated with different land uses (e.g., livestock, crops, plantations, infrastructure, recreation) or natural features (e.g., bushland, water bodies). If the property is being run as an agroforestry system with multiple land uses, plantings may be limited to previously marginal or non-productive lands. This includes roadside strips, shelterbelts, riparian buffers, hillslopes, or areas prone to erosion [61,115,217,218]. Plantings will also be influenced by the capacity of the business (size, available time, and budget), practicality, and landowner preferences. Preferences may be influenced by the location of residential dwellings, vehicle access points, firebreaks, water sources, crops treated with harmful chemicals, or crops requiring pollination [68,141,223]. Although some plantings facilitate crop pollination [47,158,224] and increase crop productivity [70], there may be a trade-off in hive health and honey quality, marketability, and production [189], when hives also service crops. It will be important to consider these, or other economic or environmental trade-offs associated with different services and land uses (e.g., [218,225]).

It will also be important to consider the local growing conditions of the site (e.g., climate, soil, hydrology, sunlight, aspect) and tailor plant choices and plantings accordingly. Native plants will be more likely to thrive under local conditions and enhance the natural biodiversity of the area [67]. They may also require fewer nutrients, water, and pest

management [67]. However, non-native plants can also be suitable options when they are non-invasive and provide economic as well as ecological benefits [62,70,226–228]. Other important considerations affecting plant choices include the availability of seeds, access to irrigation, and planting costs [6]. In some cases, planting costs can be offset by rate rebates, tax deductions, grants, and carbon credits, especially if the plants are important conservation flora. However, the plants' maintenance requirements (including costs) and ease of restoration also need to be considered. Menz et al. [49] established a framework for selecting plants based on pollinator attraction and ease of restoration. However, the framework was developed for restoring the plant-pollinator community structure. Habitat enhancement for the honey industry also needs to account for honey production and is bound by industry standards (e.g., B-QUAL) and market prices. Market prices and honey flows are unpredictable because they depend on market trends, land management practices, and climatic conditions [189,229]. For this reason, the industry needs to adopt flexible management practices [229] and establish a diversity of resources, products, and services, to spread risks and provide alternative incomes [230–232]. This may include offering pollination services or selling livestock [189,229]; growing honey plants with multiple uses including timber, pulp, fibre, firewood, biofuel, essential oils, fodder for stock, cut flowers and edible fruit, seeds, or grains [68,194,233,234]; or planting visual appealing mixtures of plants to attract visitors for agritourism [45].

9. Conclusions

The honey and pollination industries, which are closely interconnected, are currently constrained by a lack of floral resources. Resource limitations are a significant bottleneck for the industry and threaten global food security. The targeted restoration of sites with high-value and high-yielding forage would increase resources and economic opportunities for apiarists and landowners. However, methods to inform decisions about what species to plant, how many to plant, where to plant them, and how many hives the plants may support are lacking. We propose a new approach, centred on a model predicting honey production, based on the production and phenology of the flowering plants at the site and the population dynamics, resource requirements, and foraging behaviour of the managed colonies. The new approach could be used by apiarists, growers, agronomists, landowners, researchers, and policymakers to understand and predict the effect of different plant and hive scenarios on honey production, thus informing restoration and management decisions and improving outcomes for the industry, particularly as the quality and availability of nectar, pollen, and flowering data increases. The new approach supports the adoption of sustainable practices within the industry so that it can continue to meet growing demands for pollination services and honey-bee products. This is important now and in the future as apiarists face the challenge of diminishing floral resources.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/su13116109/s1>, Supplementary Appendix SA: Literature on important honey plants utilised by Australian apiarists, with a particular focus on honey plants utilised by apiarists on the Swan Coastal Plain, in the South-West of Western Australia.

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References

1. FAO. Value of Agricultural Production. FAOSTAT. Available online: <http://www.fao.org/faostat/en/#data/QV> (accessed on 7 June 2019).
2. Clarke, M. *Bushfire Recovery Plan: Understanding What Needs to Be Done to Ensure the Honey Bee and Pollination Industry Recovers from the 2019-20 Bushfire Crisis*; AgriFutures Australia: Wagga Wagga, NSW, Australia, 2020; p. 37.
3. Crane, E. When important honey plants are invasive weeds. *Bee World* **1981**, *62*, 28–30. [[CrossRef](#)]
4. Smart, M.D.; Pettis, J.S.; Euliss, N.; Spivak, M.S. Land use in the Northern Great Plains region of the US influences the survival and productivity of honey bee colonies. *Agric. Ecosyst. Environ.* **2016**, *230*, 139–149. [[CrossRef](#)]
5. Crenna, E.; Sala, S.; Polce, C.; Collina, E. Pollinators in life cycle assessment: Towards a framework for impact assessment. *J. Clean. Prod.* **2017**, *140*, 525–536. [[CrossRef](#)]
6. Isaacs, R.; Williams, N.; Ellis, J.; Pitts-Singer, T.L.; Bommarco, R.; Vaughan, M. Integrated Crop Pollination: Combining strategies to ensure stable and sustainable yields of pollination-dependent crops. *Basic Appl. Ecol.* **2017**, *22*, 44–60. [[CrossRef](#)]
7. Kovacs-Hostyanszki, A.; Espindola, A.; Vanbergen, A.J.; Settele, J.; Kremen, C.; Dicks, L.V. Ecological intensification to mitigate impacts of conventional intensive land use on pollinators and pollination. *Ecol. Lett.* **2017**, *20*, 673–689. [[CrossRef](#)] [[PubMed](#)]
8. Aizen, M.A.; Harder, L.D. The global stock of domesticated honey bees is growing slower than agricultural demand for pollination. *Curr. Biol.* **2009**, *19*, 915–918. [[CrossRef](#)] [[PubMed](#)]
9. Panța, N.D. A review of farm sustainability assessment methods: Are they applicable to the beekeeping sector? In Proceedings of the International Management Conference, Bucharest, Romania, 1–2 November 2018; Popa, I., Dobrin, C., Ciocoiu, C.N., Eds.; Faculty of Management, Academy of Economic Studies: Bucharest, Romania, 2018; Volume 12, pp. 48–55.
10. Breeze, T.D.; Vaissiere, B.E.; Bommarco, R.; Petanidou, T.; Seraphides, N.; Kozak, L.; Scheper, J.; Biesmeijer, J.C.; Kleijn, D.; Gylstenkaerne, S.; et al. Agricultural policies exacerbate honeybee pollination service supply-demand mismatches across Europe. *PLoS ONE* **2014**, *9*, e91459. [[CrossRef](#)]
11. Oldroyd, B.P. What's killing American honey Bees? *PLoS Biol.* **2007**, *5*, 1195–1199. [[CrossRef](#)]
12. Neumann, P.; Carreck, N.L. Honey bee colony losses. *J. Apic. Res.* **2010**, *49*, 1–6. [[CrossRef](#)]
13. National Research Council. *Status of Pollinators in North America*; The National Academies Press: Washington, DC, USA, 2007. [[CrossRef](#)]
14. Van Engelsdorp, D.; Hayes, J.J.; Underwood, R.M.; Pettis, J. A survey of honey bee colony losses in the U.S., fall 2007 to spring 2008. *PLoS ONE* **2008**, *3*, e4071. [[CrossRef](#)]
15. Smith, K.M.; Loh, E.H.; Rostal, M.K.; Zambrana-Torrel, C.M.; Mendiola, L.; Daszak, P. Pathogens, pests, and economics: Drivers of honey bee colony declines and losses. *EcoHealth* **2013**, *10*, 434–445. [[CrossRef](#)] [[PubMed](#)]
16. Potts, S.G.; Biesmeijer, J.C.; Kremen, C.; Neumann, P.; Schweiger, O.; Kunin, W.E. Global pollinator declines: Trends, impacts and drivers. *Trends Ecol. Evol.* **2010**, *25*, 345–353. [[CrossRef](#)] [[PubMed](#)]
17. Vanbergen, A.J.; Baude, M.; Biesmeijer, J.C.; Britton, N.F.; Brown, M.J.F.; Brown, M.; Bryden, J.; Budge, G.E.; Bull, J.C.; Carvell, C.; et al. Threats to an ecosystem service: Pressures on pollinators. *Front. Ecol. Environ.* **2013**, *11*, 251–259. [[CrossRef](#)]
18. Goulson, D.; Nicholls, E.; Botias, C.; Rotheray, E.L. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* **2015**, *347*, 10. [[CrossRef](#)] [[PubMed](#)]
19. Brown, M.J.F.; Paxton, R.J. The conservation of bees: A global perspective. *Apidologie* **2009**, *40*, 410–416. [[CrossRef](#)]
20. Wright, G.A.; Nicolson, S.W.; Shafir, S. Nutritional physiology and ecology of honey bees. *Annu. Rev. Entomol.* **2018**, *63*, 327–344. [[CrossRef](#)] [[PubMed](#)]
21. Baude, M.; Kunin, W.E.; Boatman, N.D.; Conyers, S.; Davies, N.; Gillespie, M.A.K.; Morton, R.D.; Smart, S.M.; Memmott, J. Historical nectar assessment reveals the fall and rise of floral resources in Britain. *Nature* **2016**, *530*, 85–88. [[CrossRef](#)]
22. Rosenheim, J.A.; Nonacs, P.; Mangel, M. Sex ratios and multifaceted parental investment. *Am. Nat.* **1996**, *148*, 501–535. [[CrossRef](#)]
23. Roulston, T.H.; Goodell, K. The role of resources and risks in regulating wild bee populations. *Annu. Rev. Entomol.* **2011**, *56*, 293–312. [[CrossRef](#)]
24. Requier, F.; Odoux, J.F.; Henry, M.; Bretagnolle, V. The carry-over effects of pollen shortage decrease the survival of honeybee colonies in farmlands. *J. Appl. Ecol.* **2017**, *54*, 1161–1170. [[CrossRef](#)]
25. Otis, G.W. Comments about colony collapse disorder. *Am. Bee J.* **2007**, *147*, 1033–1035.
26. Van Engelsdorp, D.; Underwood, R.; Caron, D.; Hayes, J., Jr. An estimate of managed colony losses in the winter of 2006–2007: A report commissioned by the apiary inspectors of America. *Am. Bee J.* **2007**, *147*, 599–603.
27. Naug, D. Nutritional stress due to habitat loss may explain recent honeybee colony collapses. *Biol. Conserv.* **2009**, *142*, 2369–2372. [[CrossRef](#)]
28. Smart, M.D.; Pettis, J.S.; Rice, N.; Browning, Z.; Spivak, M. Linking measures of colony and individual honey bee health to survival among apiaries exposed to varying agricultural land use. *PLoS ONE* **2016**, *11*, 28. [[CrossRef](#)]
29. Farrar, C.L. The influence of colony populations on honey production. *J. Agric. Res.* **1937**, *54*, 945–954.

30. Harbo, J.R. Worker-bee crowding affects brood production, honey production, and longevity of honey-bees (Hymenoptera, Apidae). *J. Econ. Entomol.* **1993**, *86*, 1672–1678. [CrossRef]
31. Eckert, J.E. The flight range of the honeybee. *J. Agric. Res.* **1933**, *47*, 257–285.
32. Visscher, P.K.; Seeley, T.D. Foraging strategy of honeybee colonies in a temperate deciduous forest. *Ecology* **1982**, *63*, 1790–1801. [CrossRef]
33. Dukas, R.; Edelstein-Keshet, L. The spatial distribution of colonial food provisioners. *J. Theor. Biol.* **1998**, *190*, 121–134. [CrossRef]
34. Moritz, R.F.A.; Southwick, E.E. *Bees as Superorganisms*; Springer: Berlin/Heidelberg, Germany, 1992; p. 395.
35. Tomlinson, S.; Dixon, K.W.; Didham, R.K.; Bradshaw, S.D. Landscape context alters cost of living in honeybee metabolism and feeding. *Proc. Biol. Sci.* **2017**, *284*. [CrossRef]
36. Al-Ghamdi, A.; Adgaba, N.; Getachew, A.; Tadesse, Y. New approach for determination of an optimum honeybee colony's carrying capacity based on productivity and nectar secretion potential of bee forage species. *Saudi J. Biol. Sci.* **2016**, *23*, 92–100. [CrossRef] [PubMed]
37. Otto, C.R.V.; Zheng, H.; Gallant, A.L.; Iovanna, R.; Carlson, B.L.; Smart, M.D.; Hyberg, S. Past role and future outlook of the Conservation Reserve Program for supporting honey bees in the Great Plains. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 7629–7634. [CrossRef] [PubMed]
38. Cane, J.H.; Tepedino, V.J. Gauging the effect of honey bee pollen collection on native bee communities. *Conserv. Lett.* **2017**, *10*, 205–210. [CrossRef]
39. Manning, R. *Honey Production Economic Value and Geographical Significance of Apiary Sites in Western Australia: Final Report*; Western Australian Department of Agriculture: South Perth, WA, Australia, 1992; p. 132.
40. Somerville, D. *Forestry Plantations and Honeybees*; RIRDC: Barton, ACT, Australia, 2010; p. 29.
41. FAO. Live Animals. FAOSTAT. Available online: <http://www.fao.org/faostat/en/#data/QA> (accessed on 7 June 2019).
42. Ricketts, T.H.; Regetz, J.; Steffan-Dewenter, I.; Cunningham, S.A.; Kremen, C.; Bogdanski, A.; Gemmill-Herren, B.; Greenleaf, S.S.; Klein, A.M.; Mayfield, M.M.; et al. Landscape effects on crop pollination services: Are there general patterns? *Ecol. Lett.* **2008**, *11*, 499–515. [CrossRef] [PubMed]
43. Vaudo, A.D.; Tooker, J.F.; Grozinger, C.M.; Patch, H.M. Bee nutrition and floral resource restoration. *Curr. Opin. Insect Sci.* **2015**, *10*, 133–141. [CrossRef]
44. Potts, S.G.; Imperatriz-Fonseca, V.; Ngo, H.T.; Aizen, M.A.; Biesmeijer, J.C.; Breeze, T.D.; Dicks, L.V.; Garibaldi, L.A.; Hill, R.; Settele, J.; et al. Safeguarding pollinators and their values to human well-being. *Nature* **2016**, *540*, 220–229. [CrossRef]
45. Wratten, S.D.; Gillespie, M.; Decourtye, A.; Mader, E.; Desneux, N. Pollinator habitat enhancement: Benefits to other ecosystem services. *Agric. Ecosyst. Environ.* **2012**, *159*, 112–122. [CrossRef]
46. Potts, S.G.; Vulliamy, B.; Dafni, A.; Ne'eman, G.; Willmer, P. Linking bees and flowers: How do floral communities structure pollinator communities? *Ecology* **2003**, *84*, 2628–2642. [CrossRef]
47. Brosi, B.J.; Armsworth, P.R.; Daily, G.C. Optimal design of agricultural landscapes for pollination services. *Conserv. Lett.* **2008**, *1*, 27–36. [CrossRef]
48. Haaland, C.; Naisbit, R.E.; Bersier, L.F. Sown wildflower strips for insect conservation: A review. *Insect. Conserv. Divers.* **2011**, *4*, 60–80. [CrossRef]
49. Menz, M.H.M.; Phillips, R.D.; Winfree, R.; Kremen, C.; Aizen, M.A.; Johnson, S.D.; Dixon, K.W. Reconnecting plants and pollinators: Challenges in the restoration of pollination mutualisms. *Trends Plant. Sci.* **2011**, *16*, 4–12. [CrossRef]
50. Burkle, L.A.; Delphia, C.M.; O'Neill, K.M. A dual role for farmlands: Food security and pollinator conservation. *J. Ecol.* **2017**, *105*, 890–899. [CrossRef]
51. Iovanna, R.; Ando, A.; Swinton, S.; Kagan, J.; Hellerstein, D.; Mushet, D.; Otto, C. *Chapter 1: Assessing Pollinator Habitat Services to Optimize Conservation Programs*; The Council on Food, Agricultural and Resource Economics (C-FARE): Washington, DC, USA, 2017; p. 28. [CrossRef]
52. M'Gonigle, L.K.; Williams, N.M.; Lonsdorf, E.; Kremen, C. A tool for selecting plants when restoring habitat for pollinators. *Conserv. Lett.* **2017**, *10*, 105–111. [CrossRef]
53. Eisikowitch, D.; Masad, Y. Nectar-yielding plants during the dearth season in Israel. *Bee World* **1980**, *61*, 11–18. [CrossRef]
54. Ayers, G.S.; Hoopingarner, R.A.; Howitt, A.J. Testing potential bee forage for attractiveness to bees. *Am. Bee J.* **1987**, *127*, 91–98.
55. Kigatiira, K.I.; Kahenya, W.A.; Townsend, G.F. *Prosopis* spp. as multipurpose trees in dry zones. *Bee World* **1988**, *69*, 6–11. [CrossRef]
56. Koltowski, Z.; Jabłoński, B. Attempt to develop an assortment of herbaceous honey-producing plants to be used for the improvement of bee pastures on idle lands. *J. Apic. Sci.* **2001**, *45*, 21–28.
57. Keasara, T.; Shmida, A. An evaluation of Israeli forestry trees and shrubs as potential forage plants for bees. *Isr. J. Plant. Sci.* **2009**, *57*, 49–64. [CrossRef]
58. Lonsdorf, E.; Kremen, C.; Ricketts, T.; Winfree, R.; Williams, N.; Greenleaf, S. Modelling pollination services across agricultural landscapes. *Ann. Bot.* **2009**, *103*, 1589–1600. [CrossRef]
59. Jaric, S.; Macukanovic-Jocic, M.; Mitrovic, M.; Pavlovic, P. The melliferous potential of forest and meadow plant communities on Mount Tara (Serbia). *Environ. Entomol.* **2013**, *42*, 724–732. [CrossRef]

60. Hicks, D.M.; Ouvrard, P.; Baldock, K.C.R.; Baude, M.; Goddard, M.A.; Kunin, W.E.; Mitschunas, N.; Memmott, J.; Morse, H.; Nikolitsi, M.; et al. Food for pollinators: Quantifying the nectar and pollen resources of urban flower meadows. *PLoS ONE* **2016**, *11*, 37. [[CrossRef](#)] [[PubMed](#)]
61. Ausseil, A.G.E.; Dymond, J.R.; Newstrom, L. Mapping floral resources for honey bees in New Zealand at the catchment scale. *Ecol. Appl.* **2018**, *28*, 1182–1196. [[CrossRef](#)] [[PubMed](#)]
62. Ion, N.; Odoux, J.F.; Vaissiere, B.E. Melliferous potential of weedy herbaceous plants in crop fields of Romania from 1949 to 2012. *J. Apic. Sci.* **2018**, *62*, 149–165. [[CrossRef](#)]
63. Pamminger, T.; Becker, R.; Himmelreich, S.; Schneider, C.W.; Bergtold, M. The nectar report: Quantitative review of nectar sugar concentrations offered by bee visited flowers in agricultural and non-agricultural landscapes. *PeerJ* **2019**, *7*, 15. [[CrossRef](#)] [[PubMed](#)]
64. Pamminger, T.; Becker, R.; Himmelreich, S.; Schneider, C.W.; Bergtold, M. Pollen report: Quantitative review of pollen crude protein concentrations offered by bee pollinated flowers in agricultural and non-agricultural landscapes. *PeerJ* **2019**, *7*, 13. [[CrossRef](#)] [[PubMed](#)]
65. Janssens, X.; Bruneau, E.; Lebrun, P. Prediction of the potential honey production at the apiary scale using a Geographical Information System (GIS). *Apidologie* **2006**, *37*, 351–365. [[CrossRef](#)]
66. Albayrak, A.; Duran, F.; Bayir, R. Development of intelligent decision support system using fuzzy cognitive maps for migratory beekeepers. *Turk. J. Electr. Eng. Comput. Sci.* **2018**, *26*, 2476–2488. [[CrossRef](#)]
67. Isaacs, R.; Tuell, J.; Fiedler, A.; Gardiner, M.; Landis, D. Maximizing arthropod-mediated ecosystem services in agricultural landscapes: The role of native plants. *Front. Ecol. Environ.* **2009**, *7*, 196–203. [[CrossRef](#)]
68. Leech, M. *Bee Friendly: A planting Guide for European Honeybees and Australian Native Pollinators*; RIRDC: Barton, ACT, Australia, 2012; p. 320.
69. Williams, N.M.; Ward, K.L.; Pope, N.; Isaacs, R.; Wilson, J.; May, E.A.; Ellis, J.; Daniels, J.; Pence, A.; Ullmann, K.; et al. Native wildflower plantings support wild bee abundance and diversity in agricultural landscapes across the United States. *Ecol. Appl.* **2015**, *25*, 2119–2131. [[CrossRef](#)]
70. Venturini, E.M.; Drummond, F.A.; Hoshide, A.K.; Dibble, A.C.; Stack, L.B. Pollination reservoirs for wild bee habitat enhancement in cropping systems: A review. *Agroecol. Sustain. Food Syst.* **2017**, *41*, 101–142. [[CrossRef](#)]
71. Maia, K.P.; Vaughan, I.P.; Memmott, J. Plant species roles in pollination networks: An experimental approach. *Oikos* **2019**, *128*, 1446–1457. [[CrossRef](#)]
72. Ayers, G.S.; Hoopingarner, R.A. Research imperatives for fixed-land honey production. *Am. Bee J.* **1987**, *127*, 39–41.
73. Cunningham, S.A.; Fournier, A.; Neave, M.J.; Le Feuvre, D. Improving spatial arrangement of honeybee colonies to avoid pollination shortfall and depressed fruit set. *J. Appl. Ecol.* **2016**, *53*, 350–359. [[CrossRef](#)]
74. Crane, E. *Bees and Beekeeping: Science Practice and World Resources*; Heinemann Newnes: Oxford, UK, 1990; p. 614.
75. Somerville, D. *Honey and Pollen Flora of South-Eastern Australia*; Tocal College and NSW DPI: Paterson, NSW, Australia, 2019; p. 676.
76. Crane, E.; Walker, P.; Day, R. *Directory of Important World Honey Sources*; International Bee Research Association: London, UK, 1984; p. 384.
77. Haydak, M.H. Honey bee nutrition. *Annu. Rev. Entomol.* **1970**, *15*, 143–156. [[CrossRef](#)]
78. Brodschneider, R.; Cralisheim, K. Nutrition and health in honey bees. *Apidologie* **2010**, *41*, 278–294. [[CrossRef](#)]
79. De Groot, A.P. Protein and amino acid requirements of the honey bee. *Physiol. Comp. Oecol.* **1953**, *3*, 197–285.
80. Basualdo, M.; Barragán, S.; Vanagas, L.; García, C.; Solana, H.; Rodríguez, E.; Bedascarrasbure, E. Conversion of high and low pollen protein diets into protein in worker honey bees (Hymenoptera Apidae). *J. Econ. Entomol.* **2013**, *106*, 1553–1558. [[CrossRef](#)]
81. Alaux, C.; Ducloz, F.; Crauser, D.; Le Conte, Y. Diet effects on honeybee immunocompetence. *Biol. Lett.* **2010**, *6*, 562–565. [[CrossRef](#)]
82. DeGrandi-Hoffman, G.; Chen, Y.P.; Huang, E.; Huang, M.H. The effect of diet on protein concentration, hypopharyngeal gland development and virus load in worker honey bees (*Apis mellifera* L.). *J. Insect Physiol.* **2010**, *56*, 1184–1191. [[CrossRef](#)]
83. Antúnez, K.; Invernizzi, C.; Zunino, P. Why massive honeybee colony losses do not occur in Uruguay. In *Bees: Biology Threats and Colonies*; Florio, R.M., Ed.; Nova Science Publishers: New York, NY, USA, 2012; p. 343.
84. Li, C.C.; Xu, B.H.; Wang, Y.X.; Yang, Z.B.; Yang, W.R. Protein content in larval diet affects adult longevity and antioxidant gene expression in honey bee workers. *Entomol. Exp. Appl.* **2014**, *151*, 19–26. [[CrossRef](#)]
85. Wang, H.; Zhang, S.W.; Zeng, Z.J.; Yan, W.Y. Nutrition affects longevity and gene expression in honey bee (*Apis mellifera*) workers. *Apidologie* **2014**, *45*, 618–625. [[CrossRef](#)]
86. Müller, A.; Diener, S.; Schnyder, S.; Stutz, K.; Sedivy, C.; Dorn, S. Quantitative pollen requirements of solitary bees: Implications for bee conservation and the evolution of bee-flower relationships. *Biol. Conserv.* **2006**, *130*, 604–615. [[CrossRef](#)]
87. Bozek, M. Pollen yield and pollen grain dimensions of some late-summer plant species of the Lamiaceae family. *J. Apic. Sci.* **2008**, *52*, 31–36.
88. Denisow, B. *Pollen Production of Selected Ruderal Plant Species in the Lublin Area*; University of Life Sciences in Lublin Press: Lublin, Poland, 2011; p. 86.
89. Gong, Y.B.; Huang, S.Q. Interspecific variation in pollen-ovule ratio is negatively correlated with pollen transfer efficiency in a natural community. *Plant. Biol.* **2014**, *16*, 843–847. [[CrossRef](#)]
90. Roulston, T.H.; Cane, J.H. Pollen nutritional content and digestibility for animals. *Plant Syst. Evol.* **2000**, *222*, 187–209. [[CrossRef](#)]

91. Roulston, T.H.; Cane, J.H.; Buchmann, S.L. What governs protein content of pollen: Pollinator preferences, pollen-pistil interactions, or phylogeny? *Ecol. Monogr.* **2000**, *70*, 617–643. [\[CrossRef\]](#)
92. Donkersley, P.; Rhodes, G.; Pickup, R.W.; Jones, K.C.; Power, E.F.; Wright, G.A.; Wilson, K. Nutritional composition of honey bee food stores vary with floral composition. *Oecologia* **2017**, *185*, 749–761. [\[CrossRef\]](#)
93. Filipiak, M.; Kuszewska, K.; Asselman, M.; Denisow, B.; Stawiarz, E.; Woyciechowski, M.; Weiner, J. Ecological stoichiometry of the honeybee: Pollen diversity and adequate species composition are needed to mitigate limitations imposed on the growth and development of bees by pollen quality. *PLoS ONE* **2017**, *12*, e0183236. [\[CrossRef\]](#)
94. Thakur, M.; Nanda, V. Composition and functionality of bee pollen: A review. *Trends Food Sci. Technol.* **2020**, *98*, 82–106. [\[CrossRef\]](#)
95. Herbert, E.W.; Shimanuki, H.; Caron, D. Optimum protein levels required by honey bees (Hymenoptera, Apidae) to initiate and maintain brood rearing. *Apidologie* **1977**, *8*, 141–146. [\[CrossRef\]](#)
96. Zheng, B.L.; Wu, Z.F.; Xu, B.H. The effects of dietary protein levels on the population growth, performance, and physiology of honey bee workers during early spring. *J. Insect Sci.* **2014**, *14*, 191. [\[CrossRef\]](#)
97. Kleinschmidt, G.J.; Kondos, A.C. The effect of dietary protein on colony performance. *Australas. Beekeep.* **1978**, *79*, 251–257.
98. Pernal, S.F.; Currie, R.W. Pollen quality of fresh and 1-year-old single pollen diets for worker honey bees (*Apis mellifera* L.). *Apidologie* **2000**, *31*, 387–409. [\[CrossRef\]](#)
99. Roulston, T.H.; Cane, J.H. The effect of pollen protein concentration on body size in the sweat bee *Lasioglossum zephyrum* (Hymenoptera: Apiformes). *Evol. Ecol.* **2002**, *16*, 49–65. [\[CrossRef\]](#)
100. Schmidt, J.O.; Thoenes, S.C.; Levin, M.D. Survival of honey bees, *Apis mellifera* (Hymenoptera: Apidae), fed various pollen sources. *Ann. Entomol. Soc. Am.* **1987**, *80*, 176–183. [\[CrossRef\]](#)
101. Woyke, J. Correlations and interactions between population, length of worker life and honey production by honeybees in a temperate region. *J. Apic. Res.* **1984**, *23*, 148–156. [\[CrossRef\]](#)
102. Seeley, T.D. Social foraging by honeybees: How colonies allocate foragers among patches of flowers. *Behav. Ecol. Sociobiol.* **1986**, *19*, 343–354. [\[CrossRef\]](#)
103. Pirk, C.W.W.; Boodhoo, C.; Human, H.; Nicolson, S. The importance of protein type and protein to carbohydrate ratio for survival and ovarian activation of caged honeybees (*Apis mellifera scutellata*). *Apidologie* **2010**, *41*, 62–72. [\[CrossRef\]](#)
104. Yang, W.C.; Tian, Y.Y.; Han, M.F.; Miao, X.Q. Longevity extension of worker honey bees (*Apis mellifera*) by royal jelly: Optimal dose and active ingredient. *PeerJ* **2017**, *5*, 15. [\[CrossRef\]](#)
105. Human, H.; Nicolson, S.W.; Strauss, K.; Pirk, C.W.W.; Dietemann, V. Influence of pollen quality on ovarian development in honeybee workers (*Apis mellifera scutellata*). *J. Insect Physiol.* **2007**, *53*, 649–655. [\[CrossRef\]](#)
106. Day, S.; Beyer, R.; Mercer, A.; Ogden, S. The nutrient composition of honeybee-collected pollen in Otago, New Zealand. *J. Apic. Res.* **1990**, *29*, 138–146. [\[CrossRef\]](#)
107. Somerville, D.; Nicol, H.I. Crude protein and amino acid composition of honey bee-collected pollen pellets from south-east Australia and a note on laboratory disparity. *Aust. J. Exp. Agric.* **2006**, *46*, 141–149. [\[CrossRef\]](#)
108. Nicolson, S.W.; Human, H. Chemical composition of the ‘low quality’ pollen of sunflower (*Helianthus annuus*, Asteraceae). *Apidologie* **2013**, *44*, 144–152. [\[CrossRef\]](#)
109. Loper, G.M.; Cohen, A.C. Amino-acid content of dandelion pollen, a honey-bee (Hymenoptera, Apidae) nutritional-evaluation. *J. Econ. Entomol.* **1987**, *80*, 14–17. [\[CrossRef\]](#)
110. Somerville, D. *Fat Bees Skinny Bees: A Manual on Honey Bee Nutrition for Beekeepers*; RIRDC: Barton, ACT, Australia, 2005; p. 142.
111. Manning, R. Fatty acids in pollen: A review of their importance for honey bees. *Bee World* **2001**, *82*, 60–75. [\[CrossRef\]](#)
112. Leach, M.E.; Drummond, F. A review of native wild bee nutritional health. *Int. J. Ecol.* **2018**, *10*. [\[CrossRef\]](#)
113. Tihelka, E. The immunological dependence of plant-feeding animals on their host’s medical properties may explain part of honey bee colony losses. *Arthropod Plant. Interact.* **2018**, *12*, 57–64. [\[CrossRef\]](#)
114. Asensio, I.; Vicente-Rubiano, M.; Muñoz, M.J.; Fernández-Carrión, E.; Sánchez-Vizcaíno, J.M.; Carballo, M. Importance of ecological factors and colony handling for optimizing health status of apiaries in mediterranean ecosystems. *PLoS ONE* **2016**, *11*, 18. [\[CrossRef\]](#)
115. Shrader, C.; Adamson, N.; Sole, J.; Hensley, M. *Kentucky Pollinator Handbook: A Field Office Technical Guide Reference for the Management of Pollinators and Their Habitats*; USDA: Washington, DC, USA, 2016; p. 144.
116. Waller, G.D. Evaluating responses of honey bees hymenoptera-apidae to sugar solutions using an artificial-flower feeder. *Ann. Entomol. Soc. Am.* **1972**, *65*, 857–862. [\[CrossRef\]](#)
117. Bolten, A.B.; Feinsinger, P. Why do hummingbird flowers secrete dilute nectar? *Biotropica* **1978**, *10*, 307–309. [\[CrossRef\]](#)
118. Roubik, D.W.; Buchmann, S.L. Nectar selection by *Melipona* and *Apis Mellifera* (Hymenoptera: Apidae) and the ecology of nectar intake by bee colonies in a tropical forest. *Oecologia* **1984**, *61*, 1–10. [\[CrossRef\]](#)
119. Southwick, E.E.; Loper, G.M.; Sadwick, S.E. Nectar production composition energetics and pollinator attractiveness in spring flowers of western New York. *Am. J. Bot.* **1981**, *68*, 994–1002. [\[CrossRef\]](#)
120. Kim, W.; Gilet, T.; Bush, J.W.M. Optimal concentrations in nectar feeding. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 16618–16621. [\[CrossRef\]](#)
121. Nicholls, E.; de Ibarra, N.H. Assessment of pollen rewards by foraging bees. *Funct. Ecol.* **2017**, *31*, 76–87. [\[CrossRef\]](#)
122. Van der Moezel, P.G.; Delfs, J.C.; Pate, J.S.; Loneragan, W.A.; Bell, D.T. Pollen selection by honeybees in shrublands of the northern sandplains of Western Australia. *J. Apic. Res.* **1987**, *26*, 224–232. [\[CrossRef\]](#)

123. Wills, R.T. Management of the Flora Utilised by the European Honey Bee in Kwongan of the Northern Sandplain of Western Australia. Ph.D. Thesis, Department of Botany, University of Western Australia, Perth, WA, Australia, 1989.
124. Liolios, V.; Tananaki, C.; Dimou, M.; Kanelis, D.; Goras, G.; Karazafiris, E.; Thrasyvoulou, A. Ranking pollen from bee plants according to their protein contribution to honey bees. *J. Apic. Res.* **2015**, *54*, 582–592. [\[CrossRef\]](#)
125. Waddington, K.D.; Nelson, C.M.; Page, R.E. Effects of pollen quality and genotype on the dance of foraging honey bees. *Anim. Behav.* **1998**, *56*, 35–39. [\[CrossRef\]](#) [\[PubMed\]](#)
126. Beekman, M.; Preece, K.; Schaerf, T.M. Dancing for their supper: Do honeybees adjust their recruitment dance in response to the protein content of pollen? *Insect. Soc.* **2016**, *63*, 117–126. [\[CrossRef\]](#)
127. Zarchin, S.; Dag, A.; Salomon, M.; Hendriksma, H.P.; Shafir, S. Honey bees dance faster for pollen that complements colony essential fatty acid deficiency. *Behav. Ecol. Sociobiol.* **2017**, *71*, 11. [\[CrossRef\]](#)
128. Detzel, A.; Wink, M. Attraction, deterrence or intoxication of bees (*Apis mellifera*) by plant allelochemicals. *Chemoecology* **1993**, *4*, 8–18. [\[CrossRef\]](#)
129. Nepi, M.; Grasso, D.A.; Mancuso, S. Nectar in plant-insect mutualistic relationships: From food reward to partner manipulation. *Front. Plant. Sci.* **2018**, *9*, 14. [\[CrossRef\]](#)
130. Wright, G.A.; Baker, D.D.; Palmer, M.J.; Stabler, D.; Mustard, J.A.; Power, E.F.; Borland, A.M.; Stevenson, P.C. Caffeine in floral nectar enhances a pollinator's memory of reward. *Science* **2013**, *339*, 1202–1204. [\[CrossRef\]](#)
131. Couvillon, M.; Riddell Pearce, F.C.; Accleto, C.; Fensome, K.A.; Quah, S.K.L.; Taylor, E.L.; Ratnieks, F.L.W. Honey bee foraging distance depends on month and forage type. *Apidologie* **2015**, *46*, 61–70. [\[CrossRef\]](#)
132. Free, J.B. Factors determining the collection of pollen by honeybee foragers. *Anim. Behav.* **1967**, *15*, 134–144. [\[CrossRef\]](#)
133. Dreller, C.; Page, R., Jr.; Fondrk, M. Regulation of pollen foraging in honeybee colonies: Effects of young brood, stored pollen, and empty space. *Behav. Ecol. Sociobiol.* **1999**, *45*, 227–233. [\[CrossRef\]](#)
134. Scheiner, R.; Page, R.E.; Erber, J. Sucrose responsiveness and behavioral plasticity in honey bees (*Apis mellifera*). *Apidologie* **2004**, *35*, 133–142. [\[CrossRef\]](#)
135. Danka, R.G.; Hellmich, R.L.; Rinderer, T.E.; Collins, A.M. Diet-selection ecology of tropically and temperately adapted honey bees. *Anim. Behav.* **1987**, *35*, 1858–1863. [\[CrossRef\]](#)
136. Fewell, J.H.; Winston, M.L. Colony state and regulation of pollen foraging in the honey-bee, *Apis mellifera* L. *Behav. Ecol. Sociobiol.* **1992**, *30*, 387–393. [\[CrossRef\]](#)
137. Altaye, S.Z.; Pirk, C.W.W.; Crewe, R.M.; Nicolson, S.W. Convergence of carbohydrate-biased intake targets in caged worker honeybees fed different protein sources. *J. Exp. Biol.* **2010**, *213*, 3311–3318. [\[CrossRef\]](#)
138. Bodenheimer, F.S. Studies in animal populations II: Seasonal population-trends of the honey-bee. *Q. Rev. Biol.* **1937**, *12*, 406–425. [\[CrossRef\]](#)
139. Somerville, D.; Annand, N. *Healthy Bees: Managing Pests, Diseases and other Disorders of the Honey Bee*; Department of Primary Industries: Paterson, NSW, Australia, 2014; p. 74.
140. Schmickl, T.; Crailsheim, K. Cannibalism and early capping: Strategy of honeybee colonies in times of experimental pollen shortages. *J. Comp. Physiol. A Sens. Neural Behav. Physiol.* **2001**, *187*, 541–547. [\[CrossRef\]](#)
141. Gavina, M.K.A.; Rabajante, J.F.; Cervancia, C.R. Mathematical programming models for determining the optimal location of beehives. *Bull. Math. Biol.* **2014**, *76*, 997–1016. [\[CrossRef\]](#) [\[PubMed\]](#)
142. Waddington, K.D.; Herbert, T.J.; Visscher, P.K.; Richter, M.R. Comparisons of forager distributions from matched honey bee colonies in suburban environments. *Behav. Ecol. Sociobiol.* **1994**, *35*, 423–429. [\[CrossRef\]](#)
143. Charnov, E.L. Optimal foraging, the marginal value theorem. *Theor. Popul. Biol.* **1976**, *9*, 129–136. [\[CrossRef\]](#)
144. Pyke, G.H. Optimal foraging in bumblebees: Calculation of net rate of energy intake and optimal patch choice. *Theor. Popul. Biol.* **1980**, *17*, 232–246. [\[CrossRef\]](#)
145. Hodges, C.M. Optimal foraging in bumblebees: Hunting by expectation. *Anim. Behav.* **1981**, *29*, 1166–1171. [\[CrossRef\]](#)
146. Zimmerman, M. Optimal foraging, plant density and the marginal value theorem. *Oecologia* **1981**, *49*, 148–153. [\[CrossRef\]](#)
147. Olsson, O.; Bolin, A. A model for habitat selection and species distribution derived from central place foraging theory. *Oecologia* **2014**, *175*, 537–548. [\[CrossRef\]](#)
148. Steffan-Dewenter, I.; Kuhn, A. Honeybee foraging in differentially structured landscapes. *Proc. R. Soc. B Biol. Sci.* **2003**, *270*, 569–575. [\[CrossRef\]](#)
149. Carvell, C.; Jordan, W.C.; Bourke, A.F.G.; Pickles, R.; Redhead, J.W.; Heard, M.S. Molecular and spatial analyses reveal links between colony-specific foraging distance and landscape-level resource availability in two bumblebee species. *Oikos* **2012**, *121*, 734–742. [\[CrossRef\]](#)
150. Seeley, T.D. *The Wisdom of the Hive: The Social Physiology of Honey Bee Colonies*; Harvard University Press: Cambridge, MA, USA, 1995; p. 295.
151. Amaya-Marquez, M. Floral constancy in bees: A revision of theories and a comparison with other pollinators. *Rev. Colomb. Entomol.* **2009**, *35*, 206–216.
152. Somerville, D. *Honey & Pollen Flora Suitable for Planting in South-Eastern NSW*; NSW Agriculture: Orange, NSW, Australia, 2002; p. 4.
153. Ohashi, K.; Yahara, T. How long to stay on, and how often to visit a flowering plant?: A model for foraging strategy when floral displays vary in size. *Oikos* **1999**, *86*, 386–392. [\[CrossRef\]](#)

154. Goulson, D. Why do pollinators visit proportionally fewer flowers in large patches? *Oikos* **2000**, *91*, 485–492. [\[CrossRef\]](#)
155. Spiesman, B.J.; Bennett, A.; Isaacs, R.; Gratton, C. Bumble bee colony growth and reproduction depend on local flower dominance and natural habitat area in the surrounding landscape. *Biol. Conserv.* **2017**, *206*, 217–223. [\[CrossRef\]](#)
156. Rathcke, B. Competition and facilitation among plants for pollination. In *Pollination Biology*; Real, L., Ed.; Academic Press: Orlando, FL, USA, 1983; pp. 305–329.
157. Williams, S.A. *Beekeeper's Guide to Australian Leptospermum Trees and Honey*; School of Science and Engineering, University of the Sunshine Coast: Sippy Downs, QLD, Australia, 2018; p. 185.
158. Ye, Z.M.; Dai, W.K.; Jin, X.F.; Gituru, R.W.; Wang, Q.F.; Yang, C.F. Competition and facilitation among plants for pollination: Can pollinator abundance shift the plant–plant interactions? *Plant. Ecol.* **2014**, *215*, 3–13. [\[CrossRef\]](#)
159. Adeva, J.J.G. Simulation modelling of nectar and pollen foraging by honeybees. *Biosyst. Eng.* **2012**, *112*, 304–318. [\[CrossRef\]](#)
160. Becher, M.A.; Grimm, V.; Thorbek, P.; Horn, J.; Kennedy, P.J.; Osborne, J.L. BEEHAVE: A systems model of honeybee colony dynamics and foraging to explore multifactorial causes of colony failure. *J. Appl. Ecol.* **2014**, *51*, 470–482. [\[CrossRef\]](#)
161. Agatz, A.; Kuhl, R.; Miles, M.; Schad, T.; Preuss, T.G. An evaluation of the BEEHAVE model using honey bee field study data: Insights and recommendations. *Environ. Toxicol. Chem.* **2019**, *38*, 2535–2545. [\[CrossRef\]](#)
162. Martin, S.J. The role of Varroa and viral pathogens in the collapse of honeybee colonies: A modelling approach. *J. Appl. Ecol.* **2001**, *38*, 1082–1093. [\[CrossRef\]](#)
163. Schmickl, T.; Crailsheim, K. HoPoMo: A model of honeybee intracolony population dynamics and resource management. *Ecol. Model.* **2007**, *204*, 219–245. [\[CrossRef\]](#)
164. European Food Safety Authority. Statement on the suitability of the BEEHAVE model for its potential use in a regulatory context and for the risk assessment of multiple stressors in honeybees at the landscape level. *EFSA J.* **2015**, *13*, 92. [\[CrossRef\]](#)
165. Sumpter, D.J.T.; Pratt, S.C. A modelling framework for understanding social insect foraging. *Behav. Ecol. Sociobiol.* **2003**, *53*, 131–144. [\[CrossRef\]](#)
166. Becher, M.A.; Grimm, V.; Knapp, J.; Horn, J.; Twiston-Davies, G.; Osborne, J.L. BEESCOUT: A model of bee scouting behaviour and a software tool for characterizing nectar/pollen landscapes for BEEHAVE. *Ecol. Model.* **2016**, *340*, 126–133. [\[CrossRef\]](#) [\[PubMed\]](#)
167. Timberlake, T.P.; Vaughan, I.P.; Memmott, J. Phenology of farmland floral resources reveals seasonal gaps in nectar availability for bumblebees. *J. Appl. Ecol.* **2019**, *56*, 1585–1596. [\[CrossRef\]](#)
168. DeGrandi-Hoffman, G.; Roth, S.A.; Loper, G.L.; Erickson, E.H. BEEPOP: A honeybee population dynamics simulation model. *Ecol. Model.* **1989**, *45*, 133–150. [\[CrossRef\]](#)
169. Khoury, D.S.; Myerscough, M.R.; Barron, A.B. A quantitative model of honey bee colony population dynamics. *PLoS ONE* **2011**, *6*, 6. [\[CrossRef\]](#)
170. Khoury, D.S.; Barron, A.B.; Myerscough, M.R. Modelling food and population dynamics in honey bee colonies. *PLoS ONE* **2013**, *8*, 7. [\[CrossRef\]](#)
171. Russell, S.; Barron, A.B.; Harris, D. Dynamic modelling of honey bee (*Apis mellifera*) colony growth and failure. *Ecol. Model.* **2013**, *265*, 158–169. [\[CrossRef\]](#)
172. Betti, M.I.; Wahl, L.M.; Zamir, M. Effects of infection on honey bee population dynamics: A model. *PLoS ONE* **2014**, *9*, 12. [\[CrossRef\]](#) [\[PubMed\]](#)
173. Torres, D.J.; Ricoy, U.M.; Roybal, S. Modeling honey bee populations. *PLoS ONE* **2015**, *10*, 28. [\[CrossRef\]](#) [\[PubMed\]](#)
174. Paiva, J.; Paiva, H.M.; Esposito, E.; Morais, M.M. On the effects of artificial feeding on bee colony dynamics: A mathematical model. *PLoS ONE* **2016**, *11*, 18. [\[CrossRef\]](#)
175. Bagheri, S.; Mirzaie, M. A mathematical model of honey bee colony dynamics to predict the effect of pollen on colony failure. *PLoS ONE* **2019**, *14*, 19. [\[CrossRef\]](#)
176. Lonsdorf, E.; Ricketts, T.; Kremen, C.; Winfree, R.; Greenleaf, S.; Williams, N. Crop pollination services. In *Natural Capital: Theory and Practice of Mapping Ecosystem Services*; Kareiva, P., Daily, G.C., Polasky, S., Ricketts, T.H., Tallis, H., Eds.; Oxford University Press, Incorporated: Oxford, UK, 2011; pp. 168–187.
177. Marchand, P.; Harmon-Threatt, A.N.; Chapela, I. Testing models of bee foraging behavior through the analysis of pollen loads and floral density data. *Ecol. Model.* **2015**, *313*, 41–49. [\[CrossRef\]](#)
178. Olsson, O.; Bolin, A.; Smith, H.G.; Lonsdorf, E.V. Modeling pollinating bee visitation rates in heterogeneous landscapes from foraging theory. *Ecol. Model.* **2015**, *316*, 133–143. [\[CrossRef\]](#)
179. Baveco, J.M.; Focks, A.; Belgers, D.; van der Steen, J.J.M.; Boesten, J.J.T.I.; Roessink, I. An energetics-based honeybee nectar-foraging model used to assess the potential for landscape-level pesticide exposure dilution. *PeerJ* **2016**, *4*, 25. [\[CrossRef\]](#)
180. Gioia, P.; Hopper, S.D. A new phytogeographic map for the Southwest Australian Floristic Region after an exceptional decade of collection and discovery. *Bot. J. Linn. Soc.* **2017**, *184*, 1–15. [\[CrossRef\]](#)
181. Beard, J.S.; Chapman, A.R.; Gioia, P. Species richness and endemism in the Western Australian flora. *J. Biogeogr.* **2000**, *27*, 1257–1268. [\[CrossRef\]](#)
182. Smith, F.G. *Honey Plants in Western Australia*; Department of Agriculture and Food: Perth, WA, Australia, 1969; p. 78.
183. Goodman, R.; Kaczynski, P. *Australian Beekeeping Guide*; Rural Industries Research and Development Corporation: Barton, ACT, Australia, 2015; p. 135.

184. Sniderman, J.M.K.; Matley, K.A.; Haberle, S.G.; Cantrill, D.J. Pollen analysis of Australian honey. *PLoS ONE* **2018**, *13*, 24. [CrossRef]
185. Blyth, J.D. *Beekeeping and Land Management: Proceedings of a Workshop*; Department of Conservation and Land Management: Como, WA, Australia, 1987; p. 96.
186. Wardell-Johnson, G.; Wardell-Johnson, A.; Bradby, K.; Robinson, T.; Bateman, P.W.; Williams, K.; Keesing, A.; Braun, K.; Beckerling, J.; Burbridge, M. Application of a Gondwanan perspective to restore ecological integrity in the south-western Australian global biodiversity hotspot. *Restor. Ecol.* **2016**, *24*, 805–815. [CrossRef]
187. Government of Western Australia. 2018 Statewide Vegetation Statistics: Full Report. DBCA Statewide Vegetation Statistics. Available online: <https://catalogue.data.wa.gov.au/dataset/dbca-statewide-vegetation-statistics> (accessed on 8 April 2019).
188. Benecke, F.S. *Commercial Beekeeping in Australia*; RIRDC: Barton, ACT, Australia, 2007; p. 38.
189. Keogh, R.C.; Robinson, A.P.W.; Mullins, I.J. *Pollination Aware: The Real Value of Pollination in Australia*; Rural Industries Research and Development Corporation: Barton, ACT, Australia, 2010; p. 60.
190. Van Dijk, J.; Gomboso, J.; Levantis, C. *Australian Honey Bee Industry: 2014–15 Survey Results*; ABARES Research Report 16.18; ABARES: Canberra, ACT, Australia, 2016; p. 33.
191. Rogers, S.R.; Staub, B. Standard use of Geographic Information System (GIS) techniques in honey bee research. *J. Apic. Res.* **2013**, *52*, 47. [CrossRef]
192. Abou-Shaara, H.F. Geographical information system for beekeeping development. *J. Apic. Sci.* **2019**, *63*, 5–16. [CrossRef]
193. Macintyre, P.; van Niekerk, A.; Mucina, L. Efficacy of multi-season Sentinel-2 imagery for compositional vegetation classification. *Int. J. Appl. Earth Obs. Geoinf.* **2020**, *85*, 10. [CrossRef]
194. Ferreira, C. *A Place in the Country*; Fremantle Press: North Fremantle, WA, USA, 2018; p. 272.
195. Ritchie, A.L.; Svejcar, L.N.; Ayre, B.M.; Bolleter, J.; Brace, A.; Craig, M.D.; Davis, B.; Davis, R.A.; Van Etten, E.J.B.; Fontaine, J.B.; et al. A threatened ecological community: Research advances and priorities for Banksia woodlands. *Aust. J. Bot.* **2021**, *69*, 111. [CrossRef]
196. Prober, S.M.; Byrne, M.; McLean, E.H.; Steane, D.A.; Potts, B.M.; Vaillancourt, R.E.; Stock, W.D. Climate-adjusted provenancing: A strategy for climate-resilient ecological restoration. *Front. Ecol. Evol.* **2015**, *3*, 5. [CrossRef]
197. Yates, C.J.; McNeill, A.; Elith, J.; Midgley, G.F. Assessing the impacts of climate change and land transformation on Banksia in the South West Australian Floristic Region. *Divers. Distrib.* **2010**, *16*, 187–201. [CrossRef]
198. Law, B.; Mackowski, C.; Schoer, L.; Tweedie, T. Flowering phenology of myrtaceous trees and their relation to climatic, environmental and disturbance variables in northern New South Wales. *Austral. Ecol.* **2000**, *25*, 160–178. [CrossRef]
199. Crane, E. What makes a good honey plant? *Bee World* **1975**, *56*, 32–34. [CrossRef]
200. Ayers, G.S. How much honey can you get from an acre of land? *Am. Bee J.* **1992**, *132*, 583–585.
201. Traynor, J. Evaluating pollen production of plants (with sample calculations for almonds). *Am. Bee J.* **2001**, *141*, 287–288.
202. Lupo, A.; Eisikowitch, D. *Eucalyptus erythrocorys*: A source of nectar and pollen for honey bees in Israel. *Apidologie* **1990**, *21*, 25–33. [CrossRef]
203. Corbet, S.A. Nectar sugar content: Estimating standing crop and secretion rate in the field. *Apidologie* **2003**, *34*, 1–10. [CrossRef]
204. Masierowska, M.L. Floral nectaries and nectar production in brown mustard (*Brassica juncea*) and white mustard (*Sinapis alba*) (Brassicaceae). *Plant. Syst. Evol.* **2003**, *238*, 97–107. [CrossRef]
205. Alqarni, A.S. Honeybee foraging, nectar secretion, and honey potential of wild jujube trees, *Ziziphus nummularia*. *Neotrop. Entomol.* **2015**, *44*, 232–241. [CrossRef]
206. Woinarski, J.C.; Connors, G.; Franklin, D.C. Thinking honeyeater: Nectar maps for the Northern Territory, Australia. *Pac. Conserv. Biol.* **2000**, *6*, 61–80. [CrossRef]
207. Opler, P.A. Nectar production in a tropical ecosystem. In *The Biology of Nectaries*; Bentley, B., Elias, T., Eds.; Columbia University Press: New York, NY, USA, 1983; pp. 30–79.
208. Adams, G. *Birdscaping Australian Gardens: A Guide to Native Plants and the Garden Birds They Attract*; D&G Publishing: Vaucluse, NSW, Australia, 2011; p. 364.
209. Paton, D.C. The diet of the New Holland honeyeater, *Phylidonyris novaehollandiae*. *Aust. J. Ecol.* **1982**, *7*, 279–298. [CrossRef]
210. Arora, R.K. *Optimization: Algorithms and Applications*; CRC Press LLC: Boca Raton, FL, USA, 2015; p. 466.
211. Kirkpatrick, S.; Gelatt, C.D.; Vecchi, M.P. Optimization by simulated annealing. *Science* **1983**, *220*, 671–680. [CrossRef]
212. Coloni, A.; Dorigo, M.; Maffioli, F.; Maniezzo, V.; Righini, G.; Trubian, M. Heuristics from nature for hard combinatorial optimization problems. *Int. Trans. Oper. Res.* **1996**, *3*, 1–21. [CrossRef]
213. Michalak, K. Evolutionary algorithm with a directional local search for multiobjective optimization in combinatorial problems. *Optim. Methods Softw.* **2016**, *31*, 392–404. [CrossRef]
214. Kaim, A.; Cord, A.F.; Volk, M. A review of multi-criteria optimization techniques for agricultural land use allocation. *Environ. Model. Softw.* **2018**, *105*, 79–93. [CrossRef]
215. Pannell, D.J. Sensitivity analysis of normative economic models: Theoretical framework and practical strategies. *Agric. Econ.* **1997**, *16*, 139–152. [CrossRef]
216. Madavan, N.K. Multiobjective optimization using a Pareto differential evolution approach. In Proceedings of the 2002 Congress on Evolutionary Computation, Honolulu, HI, USA, 12–17 May 2002; pp. 1145–1150. [CrossRef]
217. Hill, D.B.; Webster, T.C. Apiculture and forestry (bees and trees). *Agrofor. Syst.* **1995**, *29*, 313–320. [CrossRef]

218. Dominati, E.J.; Maseyk, F.J.F.; Mackay, A.D.; Rendel, J.M. Farming in a changing environment: Increasing biodiversity on farm for the supply of multiple ecosystem services. *Sci. Total Environ.* **2019**, *662*, 703–713. [\[CrossRef\]](#)
219. Ouvrard, P.; Transon, J.; Jacquemart, A.L. Flower-strip agri-environment schemes provide diverse and valuable summer flower resources for pollinating insects. *Biodivers. Conserv.* **2018**, *27*, 2193–2216. [\[CrossRef\]](#)
220. Sugden, E.A.; Thorp, R.W.; Buchmann, S.L. Honey bee-native bee competition: Focal point for environmental change and apicultural response in Australia. *Bee World* **1996**, *77*, 26–44. [\[CrossRef\]](#)
221. De-Miguel, S.; Pukkala, T.; Yeşil, A. Integrating pine honeydew honey production into forest management optimization. *Eur. J. Res.* **2014**, *133*, 423–432. [\[CrossRef\]](#)
222. Ausseil, A.G.E.; Dymond, J.R.; Kirschbaum, M.U.F.; Andrew, R.M.; Parfitt, R.L. Assessment of multiple ecosystem services in New Zealand at the catchment scale. *Environ. Model. Softw.* **2013**, *43*, 37–48. [\[CrossRef\]](#)
223. Gulliford, B. *Beekeeping for Business and Pleasure*; NSW Agriculture and Fisheries: Paterson, NSW, USA, 1989.
224. Ghazoul, J. Floral diversity and the facilitation of pollination. *J. Ecol.* **2006**, *94*, 295–304. [\[CrossRef\]](#)
225. Lawes, R.; Renton, M. Gaining insight into the risks, returns and value of perfect knowledge for crop sequences by comparing optimal sequences with those proposed by agronomists. *Crop. Pasture Sci.* **2015**, *66*, 622–633. [\[CrossRef\]](#)
226. Ewel, J.J.; Putz, F.E. A place for alien species in ecosystem restoration. *Front. Ecol. Environ.* **2004**, *2*, 354–360. [\[CrossRef\]](#)
227. Shackelford, N.; Hobbs, R.J.; Heller, N.E.; Hallett, L.M.; Seastedt, T.R. Finding a middle-ground: The native/non-native debate. *Biol. Conserv.* **2013**, *158*, 55–62. [\[CrossRef\]](#)
228. Blaix, C.; Moonen, A.C.; Dostatny, D.F.; Izquierdo, J.; Le Corff, J.; Morrison, J.; Von Redwitz, C.; Schumacher, M.; Westerman, P.R. Quantification of regulating ecosystem services provided by weeds in annual cropping systems using a systematic map approach. *Weed Res.* **2018**, *58*, 151–164. [\[CrossRef\]](#)
229. Kouchner, C.; Ferrus, C.; Blanchard, S.; Decourtye, A.; Basso, B.; Le Conte, Y.; Tchamitchian, M. Bee farming system sustainability: An assessment framework in metropolitan France. *Agric. Syst.* **2019**, *176*, 8. [\[CrossRef\]](#)
230. Barbieri, C.; Mahoney, E. Why is diversification an attractive farm adjustment strategy?: Insights from Texas farmers and ranchers. *J. Rural Stud.* **2009**, *25*, 58–66. [\[CrossRef\]](#)
231. Darnhofer, I.; Bellon, S.; Dedieu, B.; Milestad, R. Adaptiveness to enhance the sustainability of farming systems: A review. *Agron. Sustain. Dev.* **2010**, *30*, 545–555. [\[CrossRef\]](#)
232. Martin, G.; Magne, M.A. Agricultural diversity to increase adaptive capacity and reduce vulnerability of livestock systems against weather variability—A farm-scale simulation study. *Agric. Ecosyst. Environ.* **2015**, *199*, 301–311. [\[CrossRef\]](#)
233. Crane, E. Some multipurpose trees that are important honey sources in the tropics and subtropics. In Proceedings of the Third International Conference on Apiculture in Tropical Climates, Nairobi, Kenya, 5–9 November 1984; International Bee Research Association: Nairobi, Kenya, 1984; pp. 192–197.
234. Ayers, G.S.; Ayers, S. Bee forages with other uses part II: Plants with marketable value. *Am. Bee J.* **1997**, *137*, 651–656.