Final Report

Development of non-invasive methods and systems for the assessment of hive health

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Development of non-invasive methods and systems for the assessment of hive health (PH17001)

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Contents

Public summary

Demand for honeybees for pollination services in Australia is estimated at 650,000 hives (~A$82 million) and will increase significantly in the next decade (Clarke and Le Feuvre 2023). Demand for hives is greatest in the almond industry, estimated to reach 400,000 hives by 2026.

Almond industry contracts for hive supply include standards on 'hive strength' (number of bees in a hive). Payment to apiarists is determined by experienced auditors through inspection of hives and estimation of colony strength. However, almond growers have identified concerns with the high cost of hives, difficulties in supply of adequate hives, and that hives supplied did not meet expectations for 'hive strength' (Clarke & Le Feuvre 2023).

This project evaluated standards and conventional practices that determine colony strength and health in pollination services, and the potential use of sensing technology in monitoring of hive health and to determine colony strength to increase confidence in pollination services. These were determined through desktop studies, interviews, questionnaires, and direct field observation. A range of technology and measured parameters (e.g. temperature, hive weight) were tested against colonies of different strength in a research apiary and in hives during pollination musters.

The project found that:

- Existing standards of colony strength (8+ 'frames of bees' (FOB), queen right, disease free) are broadly applicable to pollination services within the dominant industry hive configuration of 9 frames in a 10 frame Langstroth box.
- The 'cluster count' ('number of frames' (NOF)) model (Nasr et al 1990) is widely accepted and understood, and appropriate to hive auditing.
- Cluster count audits may be flawed due to a widespread error in conversion of NOF to the 8 FOB standard on which pollination requirements in orchards are based.
- Cluster counts were confirmed to be unreliable after 9am, once bee colonies are actively foraging. Auditing relies on tacit knowledge of experienced auditors to adjustment to audits after 9am.
- Timely and consistent auditing of large numbers of hives is difficult given the increasing number of hives in use and time required to train new auditors to the required level of tacit knowledge.
- Outdated hive design and modifications may affect correct assessment of colony strength.
- Photographic audit and open-source software were developed to improve consistency in auditing, to facilitate auditor training, and to provide accurate conversion of NOF (cluster count) to FOB.
- Sensing technology can determine both hive health (dead or absconded colonies) and colony strength.
- The primary challenges to adoption of sensing technology were reported as: lack of communication networks in remote areas, high satellite communication costs, equipment costs, equipment failure, and lack of technical support.

Sensing technology and adoption developed rapidly during the project with the 2023 partnership between Bee Hero technology and Monson's Honey and Pollination (the leading brokers to the Australian almond industry).

Findings were disseminated to target audiences (industry and researchers) through industry articles and open-access peer reviewed journals, industry presentations and research conferences, webinars, video, and through the open-access publication of a PhD thesis.

Keywords

Pollination services, hive standards, almonds, hive auditing, sensing technology

Introduction

Pollination is big business. Demand for honeybee hives for pollination services in the top 10 pollination-dependent horticultural industries is estimated at around 650,000 hives (~A$82 million) (Clarke and Le Feuvre 2023). Demand is greatest in the almond industry, expected to reach approx. 400,000 hives by 2026 at an estimated cost of A$65 million.

Almost uniquely amongst horticultural industries, the almond industry contracts brokers to source and supply hives. Contracts typically include assurance on 'hive strength': an estimate of the number of bees in the hive determined by experienced auditors. Contracts may also specify number of brood frames, presence of a queen, and disease-free status (Sommerville & Frost, 2018).

Industry standards for almond pollination are based on estimates of the population of foragers that a colony provides. The population size (or 'strength') of a bee colony has been shown to correlate to the amount of pollen collected; the larger the colony (the 'stronger' the hive) the more pollen is gathered (Sheesley & Poduska 1970, Eischen et al 2007). It is then assumed that pollen collected translates to pollen visits to almond flowers and thus pollination success. However, it is important to note that the original work (Sheesley & Poduska 1970) was only designed to test the weight of pollen collected, not the relationship between colony strength and the number of foragers or foraging activity of that colony.

The number of bees in the colony ('hive strength') is typically determined by two different processes:

- Frames of Bees (FOB) or Liebefeld method: a frame-by-frame estimation of: pollen stores, brood area, and bee population each side of all frames, the presence of a queen, and disease (reviewed Dainat et al 2020)
- Number of Frames (NOF) or cluster count: a rapid audit method that estimates the the number of frames covered by 'clusters' of bees on just the top of the frames. This converts to FOB (Nasr et al 1990).

Crop pollination requirements were established based the Liebefeld calculation of 'frames of bees' (FOB), but this method is too time consuming and invasive for commercial hive auditing practice and is typically used for research and development (reviewed Dainat et al 2020). In practice the more rapid 'cluster count' (NOF) is used, modified for use in industry (Somerville & Frost 2018). The cluster count 'NOF' hould then be converted to FOB and, if correctly converted, is a good indicator of a hives population (Nasr et al 1990).

Pollination hives typically use the Langstroth design but may use one of several different configurations; single or double boxes (supers), of varying height ('depth'), and with differing number of frames in each box. Inaccuracies in translating cluster count/NOF to FOB may be introduced by variations in depth of brood box and thus frame size, where the brood box is either not a full depth box or is supplemented with an additional box that is not of full depth (Appendix 1).

Circadian rhythms and environmental factors such as temperature and daylight affect foraging by bee colonies, and as a result the cluster count should be conducted at a temperature between 7 and 15°C (Nasr et al 1990). In practice, audits should be conducted in the early morning before foraging has begun. A brokering service aims to perform audits on approximately 10% of hives in contracted services to almonds. However, the number of experienced auditors is limited, and the number of hives in use is increasing. Auditing therefor relies on the tacit knowledge of experienced auditors to make adjustment for the impacts of time of day and temperature on visible clusters. The considerable experience and time required to train new auditors to the required level of tacit knowledge limits the capacity of auditing services.

A recent survey of almond growers identified 3 key concerns with pollination services: the high cost of hives, difficulties in supply of sufficient, adequate hives to meet demand, and that hives supplied did not meet expectations for 'hive strength' (Clarke & Le Feuvre 2023). The cost and lack of confidence in auditing methods, and the potential to spread disease through repeated opening of hives, are a source of concern to both orchardists and apiarists.

The emergence of sensing technology combined with machine learning and connection of sensors in hives to apiarists through the 'internet of things' offers the prospect of non-invasive monitoring of hives in apiaries. At the start of the project, a wide range of hive sensing technology was being promoted, recording parameters such as hive weight, temperature, humidity, sound, and bee transit. Some of these had translated to commercial systems, primarily aimed at apiarists to monitor honey production and to determine issues such as colony collapse and absconding (swarming).

Sensing technology also offered the potential to determine colony strength without the drawbacks of conventional auditing, but little application was available outside of research. The link between measurable parameters and colony strength had not been credibly established for use in commercial pollination services. Issues such as placement of sensors, and the impacts of apicultural practice on baseline parameters were largely undetermined. This project addressed the needs for greater confidence in pollination services and standards, and for more information on the potential use of sensing technology in commercial practice. The project aimed to evaluate hive standards, pollination practices, and the potential use of sensing technology in key horticultural industries (almond, avocado, cucurbits, blueberry) and to disseminate findings and recommendations to horticultural industries, apiarists, pollination service providers, brokers and auditors, and research communities.

Methodology

This project evaluated hive standards, pollination service and auditing practices, and the application of sensing technology to determine hive health and colony strength. Hive standards, parameters of colony strength, and available sensing technology were examined in desktop studies. Standards, practices, and the use of sensing technology in commercial pollination services were determined through interviews, questionnaires, and direct observation in the field. Sensing technology recording a range of parameters (e.g. hive temperature, humidity, hive weight, and bee transit) and the use of hand-held thermal imaging were tested to evaluate their fitness in the calculation of colony strength. Methods are summarised below, with detail in open-access references and a PhD thesis (D. Cook 2022, Appendix 1).

Desktop studies and reviews. Hive standards and hive classification systems which that define an "effective" honeybee hive for use in crop pollination, and of sensing technology, were determined through desktop reviews.

A review of New Zealand code of practice, existing Australian standards, and the practical value of hive remote monitoring equipment were completed from academic sources, industry manuals and publications. (Appendix 2 and 3). The literature review primarily used systematic search methods to locate published articles in scientific literature and agricultural databases.

A review of hive classification, auditing processes and a re-evaluation of the conversion between cluster counts (NOF) and frames of bees (FOB) was conducted from academic peer reviewed literature and industry manuals and books (Appendix 1). A horizon scan and market review of available sensors systems for beehives was also conducted (Appendix 1).

Interviews, observations, and questionnaires. Standards and practices in use in commercial pollination services were determined through interviews, questionnaires, and direct observation in the field.

Standards, practices, and use of sensing technology were determined through observation and semi-structured interviews with apiarists (n=15). Apiarists approached for interview were selected based on their engagement with large scale pollination across four primary crops (almond, avocado, blueberries, cucurbits) and owning or managing 1000+ hives. For cucurbits, apiarists with a lower number (>200) of hives were accepted due to the lack of large-scale pollinators in the industry. Audio recordings of both face-to-face and online interviews were transcribed and then analysed by two researchers using qualitative deductive coding methods (Appendix 1, Cook et al 2021).

Observation of current pollination service practices and auditing methods was conducted via a concurrent talk-aloud protocol and video observation during the hive migration from Queensland to Victoria and in almond orchards during the spring 2019 and 2020 pollination hive musters (Appendix 1).

Experimental testing. The assumptions on which hive standards for pollination services and conventional auditing practices are based were tested in research apiaries through experimental observation.
Quantifiable parameters associated with hive health and colony strength were investigated through testing of multiple sensors suites, both commercial and developed by the project.

Pollen foraging and hive strength: The population size (or 'strength') of a bee colony has been shown to correlate to the amount of pollen collected; the larger the colony (the 'stronger' the hive) the more pollen is gathered (Sheesley & Poduska 1970, Eischen et al 2007). It is then assumed that pollen collected translates to pollen visits to almond flowers and thus pollination success, but the earlier work was only designed to test the weight of pollen collected, not the relationship between colony strength and the number of foragers or foraging activity of that colony.

Experiments building on the methods of Sheesley and Poduska (1970) were conducted to assess if the relative pollen foraging activity of a colony changes in relation to colony strength. The correlation between colony strength (as FOB), the amount of pollen collected, and the number of foragers and pollen foragers were determined.

A trial was conducted with 56 Plant and Food Research research hives at two apiary sites at the Ruakura Research Centre, New Zealand. Both apiary sites used are within foraging range of flowering blueberry and kiwifruit plantings, however, are predominantly surrounded by pasture including Taraxicum, Phormium, and Trifolium as major pollen forage sources. Though the original study was undertaken in almond orchards, the relative foraging efficiency between the hives was expected to equate to the efficiency had they been deployed in a horticultural setting.

Hives were assessed as being queen right and meeting the general health requirements of pollination hives and were subsequently assessed for colony strength using the cluster count method (Nasr et al. 1990). Hives were then adjusted by removing frames of brood and bees to achieve 4 groups of hive strengths: 2, 6, 10, and 14+ (frames of bees ±.5, 7 hives per group per apiary). Hives were then assessed again to confirm the starting strength baselines.

Pollen collection can be used as a proxy for forager activity and was collected to provide direct comparison to the metrics used by Sheesley and Poduska (1970). Immediately following assessment, hives were fitted with modified Mann-Lake Superior pollen traps (internal baffles removed). Pollen samples were collected at 24-hour intervals on three subsequent days, and traps were removed 36 hours before the next forager count. Data collection continued for three weeks and final strength assessments took place on 8 December 2020.

Pollen collection may be influenced by subtle changes within a healthy hive, and measured collection rates are influenced by the efficiency of traps used (not specified in the original paper), and by the physical consistency (pellet size) of the pollen types being returned. Returning foragers were counted, a metric which is less affected by pollen types and trap designs,and incorporates all foragers (including nectar collectors) and therefore may be a more accurate measure of pollination effort. All hives were assessed weekly from November 2020 for forager activity by visual assessments of rates or return of pollen and nectar foragers.

A second experiment was conducted in the Australian research apiary in Samford, Queensland. Hives were manipulated to three different classifications based on industry practice as identified in interviews with apiarists: strong (>6 FOB bees), medium (3-6 FOB), and weak (<3 FOB). Hives were audited using the cluster count method. Forager rate and forager type were recorded by four observers. Observations were conducted on 3 non-consecutive days within a week at five time points at 2.5-hour intervals from sunrise (0600hrs) and then at 0830hrs, 1100hrs, 1330hrs, and 1600hrs. At each time point, observers were randomly assigned a selection of approximately ten hives. Observers sit or stand approximately one meter at an angle of 45° to the hive front and entrance (to avoid interrupting forager flight) and recorded the number of pollen foragers and the number of non-pollen foragers returning to the hive in a sixty second period. Pollen foragers were identified by the pollen stored within their corbiculae. Data was analysed in RStudio Team (2021). The relationship between forager activity (measured in foragers per minute) and colony strength (measured by the cluster count method) was modelled while controlling for the effect of time of day.

Auditing practice and hive strength: Experiments apiary Brisbane. The impact of time of day on the audit result was determined in two experiments in forty (n=40) hives in a research apiary in Queensland. Each hive consisted of a full-depth 10 frame Langstroth brood box containing nine full-depth frames of built-out wax comb on a plastic foundation (Appendix 1)Experiment 1 (conducted in Autumn (April) 2021) audited every hive every two hours using the modified cluster count method. Experiment 2 (conducted in spring (September 2022) assessed the impact of repeated opening on the audit result in two groups each of 17 hives. Group 1 was opened every two hours (6am, 8am, 10am, 12pm, 2pm) and audited as in Experiment 1. In the control group 2, each hive was opened only once, at 2pm. Each open hive was photographed and cluster counts were validated by a second researcher from the photographs.

Open-source software and a photographic audit process were created to improve methodological rigour and repeatability without a requirement for significant experiential and tacit knowledge, to support training of new auditors, and to facilitate the conversion of cluster counts to FOB. Data from two existing audit methods and three novel assessment methods including cluster count and full frame of bees were evaluated against actual hive data and against sensing technology and parameters. Photographs of audits were evaluated by 3 independent auditors. Between-method conversion factors were determined using linear modelling to provide a single-click conversion between assessment methods (such as cluster count to FoB). The software was coded in Python, released on an open license and stored on Github (Cook & Hauxwell 2024 *in press*).

Baseline data on colony parameters from sensing technology during apicultural practice were determined. Custom designed sensors systems and Maxim Integrated Hygrochron iButtons were used to quantify the thermal impacts of apicultural practices on the hive (Cook et al. 2021a, Appendix 1).

Lolligo “blueberry” sensors were used to collect temperature, humidity, light and acceleration data to determine the impacts of apicultural practice and migratory hive practice on colony homeostasis during hive migration from Queensland to Victoria in 2019 and 2020, in almond orchards during the spring 2019 and 2020 pollination seasons, and in avocado orchards during the 2020 season (Appendix 1)

Evaluation of sensing technology to determine 'hive strength'
Temperature, humidity, weight and bee counts: Initial experiments were conducted at a Brisbane commercial apiary using twenty leased hives set to an industry standard configuration: a ten frame Langstroth deep brood box containing nine frames and a super containing 9 frames. The omission of a frame is a common practice to facilitate inspections. Temperature, humidity, weight and bee counts were measured across twenty hives and compared to industry standard cluster-count strength measurement (Appendix 1). Maxim Integrated Hygrochron iButtons were used to measure in-hive temperature and humidity at varying sampling rates. Prototype Ecrotek sensors systems were used to measure weight and forager activity (bee transit), but were discontinued due to difficulties in maintaining functional systems.

Custom designed sensors systems were then developed and used to monitor multi-point temperature within the hive (Cook et al. 2021a, Appendix 1). These contributed to implementing and evaluating sensor systems in beehives.

Sensing technology measuring selected parameters were then evaluated in a research apiary in Queensland. The hives were equipped with a standard deep ventilated lid and an Ecrotek 'Hive Doctor' ventilated base. Forty of the hives were confirmed disease-free and queen-right, while two hives without an active bee colony were used as controls. Colony strength was determined using the cluster count method (Nasr et al.'s (1990). The research took place in May (early winter in Queensland), in conditions similar to those found in spring almond pollination events in southern Australia. Three audits were performed on non-consecutive days by two independent assessors using photographic validation methods, and disparities between assessments were reconciled (Appendix 1, Cook et al 2022).

Temperature sensing and hive strength: Each hive was equipped with four Maxim Integrated DS18B20 1-Wire Digital Thermometers. Data collection points were set at 5-minute intervals over 18.6 days and data processed in Microsoft Excel and R Studio. The association between temperature range, sensor position in the hive, and hive strength was investigated using linear mixed-effect models. A linear mixed-effect model was employed to compare the number of frames with hive temperature, incorporating harmonic sine and cosine curves to capture diurnal temperature patterns. Optimal sensor placement was determined from four independent linear mixed models for each sensor position, and model performance was evaluated using Akaike Information Criterion (AIC) scores. The model with the lowest AIC score was considered the most appropriate for predicting colony strength based on sensor placement (Cook et al 2022).

Thermal imaging: In interviews, several apiarists mention thermal infra-red camera trials, and some have purchased these cameras for personal inspection of hives without formal conversion to hive standards. No apiarists were actively using this technology for strength assessment. The Verifli thermal imaging and translation service (Bee Corp, USA) in use in almonds in the USA is a promising tool for hive auditors. This service used thermal imaging during the night to assess an average of colony strength for a given unit of hives, such as by drop, or by apiary source, and return the information next day as an assessment of colony strength to a phone app. Hand-held thermal imaging cameras were obtained on loan from Bee Corp and evaluated against hives of known strength in the Queensland research apiary.

Results and discussion

Significant challenges to pollination services occurred during the conduct of the project. Interstate border closures and biosecurity measures imposed during the Covid pandemic and the incursion of varroa mite had significant impacts on pollination services and on this research. Nevertheless, results and outputs were achieved.

Hive standards and classification:

Desktop studies and analysis of interviews with apiarists indicate that the '8 frames of bees' standard is established, well known, and is applied in practice. Apiarists supplying the almond industry understand the '8 frames of bees' requirement stipulated in the almond pollination contracts and aim to meet this. However, other orchardists (Avocado, Blueberry) do not appear to use contracts or colony strength audits (Cook et al. 2021a, Appendix 1).

The majority of apiarists interviewed assessed hive strength visually using experiential knowledge of what constitutes a 'strong' colony. This was based on factors such as being queen-right with a good brood pattern, adequate honey and pollen stores, not honey-bound (when nectar stores clog up the brood nest), and with a large population of bees rather than measures such as cluster counts. Strength categories used by apiarists typically fell into 3 categories: strong, weak, and problem hives (diseased, without queen etc) (Appendix 1).

The standard of 8 frames of bees (in a 10 frame full-depth Langstroth box with 9 frames of comb) were on the whole supported by experimental observations. Results of the New Zealand study confirmed earlier work showing that stronger hives return a greater amount of pollen to the hive. The total number of both foragers and pollen foragers increased with increasing colony strength (FOB) in both the New Zealand and Australian experiments, with stronger hives contributing a larger absolute number of foraging bees.

A significant finding was the variability in hive construction (particularly depth of boxes) and configuration (frames per box) driven by poor ergonomic design. A honey-laden full-depth ten frame box weight more than 35kg. Several apiarists reported using half-depth honey boxes as it is "easier on the back", and all apiarists interviewed immediately added "lifting cleats" to make the unit usable. The need for lighter honey hives (particularly wooden boxes) leads to modifications that, if used in pollination services, impact auditing and colony strength estimations and to delivery on 'non standard' hives. Since many hives are also multi-function, for both honey and pollination, does occur in pollination hives.

A further significant indicator of poor product-function fit is the widespread use of nine frames of comb in the "standard" ten frame box. All apiarists using 10-frame Langstroth boxes reporting that ten frames were 'too tight', which risks breaking the frames and crushing bees. In practice then, '8 frames of bees' equates to a 'full box of bees' using the standard full-depth 10 frame Langstroth box with frames, with bees covering 8 out of 9 frames and sufficient space to inhibit swarming (Cook et al. 2021, Appendix 1).

There are some important results from both the Australian and New Zealand studies. The New Zealand study found a small but significant inverse relationship between 'hive strength' (FOB) and proportion of bees foraging. 'Weaker' hives (4 FOB) devoted a higher relative proportion of their total number of workers to foraging than larger colonies (8+ FOB).

In the Australian study, both pollen and forager counts increase between 6am (dawn) and 9am. Counts of foragers per minutes remain largely stable between 9am and 4pm (Appendix 1). There was again an apparent increase in proportion of pollen foragers in 'weaker' hives: approximately 5 pollen foragers per minute were observed at the entrance of a hive with 1 FOB, while approximately 15 bees are observed for a hive with 12 FOB. This represents only a 3X increase in the output of pollen foragers per hive for a 12X increase in FOB.

These observations should be interpreted with caution. Weak hives (less than 3 frames bees) contribute fewer total bees to foraging and returned less total pollen to the hive than strong hives and the value of 'weak' hives to commercial pollination services for is questionable. Other factors need to be taken into account, including the depth of box and total number of frames, such 9 frames in a 10 frame Langstroth box. However, very strong hives (>8 FOB) appear to show no further change in number of foragers relative to total worker bees, and the additional costs where a second box of 9 frames is added (resulting in >9 FOB) must be weighed against other criteria including presence of brood and queen, nutrition, and space within the hive, and transport of potentially half-filled second boxes.

Crops could be classified into nectar and pollen driven crops, where either the nectar or pollen was the priority for foraging bees. Almond is a 'pollen driven' crop, while macadamia, avocado and apple are 'nectar driven'. This has potential for the manipulation of bee colonies into pollen- or nectar-driven by increasing or decreasing the amount of brood present in the hive to drive priority for pollen collection by the foragers. Manipulation of hives to match these drivers to the crop was not seen in practice (Appendix 1).

Auditing processes and practice. The greatest disjunction between standards and practice was found in the application of standards in auditing. The accepted industry model of colony strength assessment, the cluster count method, is widespread and applied in industry (Nasr et al.1990, Appendix 1). However, a review of literature and industry guidelines found that in Australia this method is incorrectly applied. A regression equation is required to convert between cluster count NOF and FOB on which most crop pollinator requirements are based (Nasr et al. 1990). In Australia, this conversion from NOF to FOBs is widely omitted. As a result, audits may significantly overestimate strength of weak colonies (Appendix 1, Cook & Hauxwell 2024 *in press*).

Furthermore, experimental assessment confirmed that cluster count (NOF) decreases after approximately 9am under conditions of temperature and daylength similar to those in spring in almond orchards. Strong colonies exhibit the greatest reduction in cluster count during the day. The net effect was that by late morning, the cluster count in strong hives was not significantly different from the 6am count of medium hives. By 4pm the cluster count was not significantly different in any of the hives (Appendix 1). Audits conducted later in the day have the potential to underestimate the strength of stronger hives.

Observations of hive audits in the two musters demonstrated that while the audit process was extremely fast, a large proportion of time was spent accessing the frames and recording observations. Commercial audits must audit a large number of hives (10% of a large and increasing total). Timely and consistent auditing of large numbers of hives is thus challenging due to the increasing number of hives and lengthy process required to train new auditors to the required level of tacit knowledge. We cannot discount 'tacit knowledge' in this process. Experienced cluster-count auditors adjust their evaluation based on time of day. However, some additional Q/A will be increasingly required as demand (and prices) for hives increases.

The project created and validated a photographic audit and open-source software to identify, count, and convert cluster counts to FOB or total number of bees (and vice versa). Photographs of open hives can be taken rapidly in the field and inspected later in the day by one or multiple viewers to identify and count clusters of bees with minimal training, and can be used to assist in training of new auditors. The process and software is described in an online video. The software, coded in python, is released under an open license for others to use, edit or adapt. It can be accessed on Github at: https://github.com/illuminateddan/Cluster-Count-Audit-Software/. Development and validation is detailed in Cook & Hauxwell (2024 *in press*).

Outside of almond brokers, hive auditors (such as BQUAL) audit the practices and standards of the apiarists, not the hives delivered. An alternative to auditing hives on delivery may be to audit and certify registered apiarists, who's standards and practices deliver good quality 'strong' hives and who are paid a premium for that service. This is effectively the result of the 2023 partnership between Bee Hero and Monson's Honey and Pollination (the leading brokers to the Australian almond industry). Bee Hero's multi-parameter in-hive sensing and AI-assisted data analytics model provide identification of problem (e.g. diseased, absconded) hives and an estimate of hive strength as a fee for service to apiarists. Apiarists licensing the technology are then contracted for almond pollination without further auditing on delivery.

Sensing technology, cost/benefit and industry fit: None of the participants in interviews and questionnaires reported using technology at scale, but there was a level of interest and curiosity. Four participants had conducted small-scale trials of various systems, including combinations of hive weight sensors, temperature, and rain-sensing. Weight sensors (individual hive scales) were the most widespread technology in use in commercial honey hives. Their use in remote hives was used to schedule operations such as supering or honey removal, optimizing time and reducing transport costs (a significant expense in widely distributed beekeeping operations). Weight sensing technology also facilitated colony health monitoring, detecting swarming (absconding) and disease indicated by a sudden drop in weight. Rain gauges were utilized for weather monitoring. Several participants discussed the potential use of Forward-Looking Infra-Red (FLIR) thermal camera technology to estimate colony strength, but only one participant had actively engaged in trials.

Most hive sensor systems, e.g. Hivemind and Arnia, provide raw data to users, leaving it to the apiarist to interpret the outputs. These systems were perceived by interviewed apiarists as not providing sufficiently useful information. Participants used the observed sensor outputs, combined with their experiential knowledge, to make assumptions about hive activity and health, but did not determine colony strength as defined in pollination services.

The challenges highlighted by participants in using technology were the lack of communication networks in remote areas, high satellite communication costs, equipment cost, equipment failure, and a lack of manufacturer support. The high costs associated with equipment and monitoring made individual hive monitoring impractical at that time. Several participants stated that while the technology sounded promising, it did not meet practical expectations at the time. All participants unanimously agreed that technology did not surpass experiential knowledge, expressing the sentiment that it would "never be as good as sticking your head in the box".

Nevertheless, adoption of sensing technology increased rapidly towards the end of the project with the commercial partnership between Bee Hero technology and Monson's Honey and Pollination (the leading brokers to the Australian almond industry) in 2023. Apiarists licensing the Bee Hero technology are then contracted for the almond pollination muster without further auditing on delivery. Thermal imaging (FLiR) has also increased in usage for hive inspections in apiaries, though not for standardised determination of colony strength.

The horizon scan and market review identified many systems as 'vaporware': a technology design or description without a tangible commercial product. Three available sensors systems that recorded the parameters common to the majority of sensing products (temperature, humidity, hive weight, bee transit) were included in experimental testing.

Baseline data on colony parameters from sensing technology: Custom designed sensors systems used to monitor multi-point temperature within the hive contributed to implementing and evaluating sensor systems in beehives. The research established a systematic understanding of the thermal dynamics of Langstroth beehives under various conditions and in apicultural practice (Cook et al 2021a, Appendix 1). A key finding was the significant impact of migratory hive practice on hive homeostasis and the resulting stress on bees, with impacts lasting several days during and after transport.

Evaluation of sensing technology to determine 'hive strength': Prototype Ecrotek sensors systems (weight and bee transit) were used to measure weight and bee transit, but were discontinued due to difficulties in maintaining prototype systems.

The relationship between internal hive temperature and colony strength was statistically significant. A one-unit increase in the Number of Frames correlated with an average temperature increase of 0.36°C ($p = 0.027$). Optimal sensor placement, in the centre of the lateral plane of the hive, was determined, with significant differences in recorded temperature range across the four sensor placement positions. Temperature sensing was also able to detect collapse or absconding (swarming) of bees: hives without active bee colonies exhibited an average temperature 5.55°C lower than hives with bees ($p = 3.87e\text{-}5$). (Cook et al 2022,Appendix 1).

Photos/images/other audio-visual material

Cook, D. 2023. Cluster counter v1.0 software video: https://www.youtube.com/watch?v=k9dWufk_S24
Centre for Agriculture and Bioeconomy, Queensland University of Technology Seminar Series. (2021). Beyond Honey: Improvements in beekeeping to optimize pollination and food security. Passcode: H8#83dz$
Cook, D. 2022. An examination of pollination and practice in Australian apiculture. PhD final seminar, Queensland University of Technology.
Cook 2021. Thermal impact of apiculture on the bee colony. Tocal college, NSW. October 2021. https://www.youtube.com/watch?v=CeEIRVyu-bg&ab_channel=NSWTocalCollege
Cook 2021. Apiculture practice and products: an inter-disciplinary industry project. Project overview, QUT Design for Change. August 2022. https://www.youtube.com/watch?v=5G2cv9Fa_E0

Outputs

This project addressed the demand from horticultural industries for greater confidence in pollination services through evaluation and dissemination of information on hive standards, commercial pollination practices, and potential and actual use of sensing technology to determine colony health and, more specifically, hive strength in key horticultural industries (almond, avocado, cucurbits, blueberry). Findings and recommendations were widely disseminated to industry (orchardists, apiarists, pollination service providers, and researchers) through the media, webinars, industry meetings and conferences, industry publications, open-source peer reviewed publications, and an open-source PhD thesis.

Table 1. Output summary

Output	**Description**	**Detail**
1. A **classification system** will be designed and evaluated to **define an "effective" colony for pollination** of key Australian crops through industry consultation, design research methods, and literature reviews.	Standards of 'queen right' and 8 FOB in a standard configuration of 9 frames in a 10 frame box were confirmed as broadly appropriate for almond (pollen-driven) pollination services Implementation of methods and models for estimation of colony strength were found to be flawed and potentially inconsistent.	Evaluation and standards are described in three papers (Cook et al., 2023a; 2023b; 2023c), a PhD thesis (Appendix 1) and appendix 2. Comparisons and field testing of industry classifications were made in Cook et al. (2023a; 2023b).
2**. A "colony strength" standard and a QA model** will be developed and evaluated. It will be designed to fit current industry practice (both grower and apiarist) and to align with the Honey Bee code of practice. A preliminary standard and QA model will be developed.	Capacity to conduct timely, consistent audits of hives is challenged by the increasing scale of hive supply and difficulty in recruitment and training of new auditors. Inconsistencies in auditing practice using the cluster count method and errors in conversion	Cluster count video: https://youtu.be/k9dWufk_S24 Cook, D., Hauxwell, C. (2024). Providing rigor in bee colony strength auditing methods. Journal of Economic Entomology. *In Press.* "How many bees in a box?". For submission to almond industry magazine 'In A Nutshell' 2024

	to FOB were addressed. Photographic audit and open-source software produced to improve consistency and accurately convert cluster counts to standard 'frames of bees'.	
3. **Quantifiable parameters of colonies** required for effective pollination services will be determined by analysis of existing practice and from analysis of data from sensing technology in hives under Australian field conditions.	Temperature, humidity, bee transit, hive weight, sensor placement, and hand-held thermal imaging technology (FLiR) were evaluated in a research apiary. Temperature sensing was used to determine impacts of hive transport and commercial practices. Temperature with appropriate sensor placement were shown to generate data that could determine colony strength.	Cook, D., Tarlinton, B., McGree, J. M., Blackler, A., & Hauxwell, C. (2022). Temperature Sensing and Honey Bee Colony Strength. Journal of Economic Entomology. https://doi.org/10.1093/jee/toac034
4. A review of **current non-invasive tools** (both domestic and overseas) at both the R&D and commercial level will be conducted. Tools will be evaluated to determine their validity in assessment of colony strength against the parameters defined above. The project will, in addition, evaluate this technology in hives and use data obtained to inform [1] and [2], above.	Multiple desktop reviews and a horizon scan were completed. A shortlist of sensing technology was evaluated in apiaries and in the field against colonies of known strength.	Appendices 1 and 3 Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2021). Thermal Impacts of Apicultural Practice and Products on the Honey Bee Colony. Journal of Economic Entomology, 114(2), 538-546. https://academic.oup.com/jee/article/114/2/538/6168215 Cook, D., Tarlinton, B., McGree, J. M., Blackler, A., & Hauxwell, C. (2022). Temperature Sensing and Honey Bee Colony Strength. Journal of Economic Entomology. https://doi.org/10.1093/jee/toac034 Cook, D., Hauxwell, C. (2024). Providing rigor in bee colony strength auditing methods. Journal of Economic Entomology. *In Press.* Cook, D., Tarlinton, B., McGree, J. M., Blackler, A., & Hauxwell, C. (2024b). Temporal bias in the cluster count bee colony audit method. *In preparation*
5. A **cost benefit analysis** and the project will **evaluate available technology** and critically evaluate it for analysis, interpretation and translation of data for the benefit of growers and apiarists.	Costs and benefits were evaluated for technology available at the time of the project. Technology was evaluated and results widely disseminated and published.	Appendices 1 and 3 Open access publications, presentations and webinars (including on line recordings) listed in this report.
6. The methodology of interviews, observation and analysis described above, will be used to **quantify grower and apiarist requirements and evaluate both the QA system and standards for colony strength and sensing technology**, in conjunction with a formal cost benefit analysis. These data will be used to modify the systems and standards to ensure best fit with industry requirements, and	Interviews and observations were completed. Hive standards were found to be broadly applicable, well understood and in use. Inconsistencies and errors in colony strength practice, calculation, and in some hive designs in use were found to impact the application of standards. Recommendations and tools to address this were developed and disseminated.	Appendices 1 and 2 Cook, D. 2023. Cluster counter v1.0 software video: https://www.youtube.com/watch?v=k9dWufk_S24 Cook, D., Hauxwell, C. (2024). Providing rigor in bee colony strength auditing methods. Journal of Economic Entomology. *In Press.* Cook, D., Tarlinton, B., McGree, J. M., Blackler, A., & Hauxwell, C. (2024b). Temporal bias in the cluster count bee colony audit method. *In preparation*

provided to manufacturers, researchers and industry to facilitate technology development that fits with grower, apiarist and horticultural business requirements.		
7. **Analysis of sensing data will be provided to manufacturers** and researchers to facilitate technology development that fits with grower, apiarist and horticultural business requirements.	Data and analysis were widely disseminated in open access publications, industry meetings and national and international conferences.	Appendix 1 Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2021). Thermal Impacts of Apicultural Practice and Products on the Honey Bee Colony. Journal of Economic Entomology, 114(2), 538-546. https://academic.oup.com/jee/article/114/2/538/6168215 Cook, D., Tarlinton, B., McGree, J. M., Blackler, A., & Hauxwell, C. (2022). Temperature Sensing and Honey Bee Colony Strength. Journal of Economic Entomology. https://doi.org/10.1093/jee/toac034
8. **The project will publish and disseminate findings** on efficacy, costs and benefits of non-invasive colony evaluation technology to industry, and disseminate findings to industry. This will include presentation at appropriate grower and apiarist forums and articles in industry publications.	Findings and recommendations were widely disseminated to industry, orchardists, apiarists, pollination service providers, and researchers	Findings were widely disseminated to industry and researchers through industry articles and open-access peer reviewed journals, industry and research conferences, webinars, on-line seminars (with accessible recordings), videos, and through the open-access publication of a PhD thesis listed in this report.

Industry presentations

Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2021). Thermal Impacts of apiculture on the bee colony. New South Wales Apiarist Association Annual Conference, Tamworth, Australia. https://eprints.qut.edu.au/211442/
Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2021). Thermal Impacts of apiculture on the bee colony. Queensland Beekeepers Association Annual Conference, Gold Coast, Australia. https://eprints.qut.edu.au/211443/
Cook, D., Blackler, A., & Hauxwell, C. (2021). The evolution of the beehive: past, present & future. Queensland Beekeepers Association Field Day, Beenleigh, Australia. https://qut.elsevierpure.com/admin/files/97833048/Histoy_of_the_beehiveV3.pptx
Cook, D., Blackler, A., & Hauxwell, C. (2021). The evolution of the beehive: past, present & future. Queensland Beekeepers Association Annual Conference, Gold Coast, Australia. https://eprints.qut.edu.au/211443/
Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2021). Thermal Impacts of apiculture on the bee colony. Melbourne Beekeeping Society. Melbourne, Australia. https://eprints.qut.edu.au/211442/
Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2021). Thermal Impacts of apiculture on the bee colony. Alameda County Beekeeping Association. San Francisco, United States of America. https://eprints.qut.edu.au/211442/
Cook, D., Blackler, A., & Hauxwell, C. (2021). The evolution of the beehive: past, present & future. Brisbane Northside Beekeepers Association, Brisbane, Australia. https://eprints.qut.edu.au/211443/
Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2022). Future for bee technology. Australian Bee Congress 2022. Sydney, Australia.
Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2022). Future of temperature sensing in hive auditing. Australian Bee Congress 2022. Sydney, Australia.
Cook, D., Tarlinton, B., McGree, J. M., Blackler, A., & Hauxwell, C. (2023). Temporal bias in the cluster count bee colony audit method. Almond Industry Forum 2023. Robinvale, Australia.

Public Seminars and Webinars

Centre for Agriculture and Bioeconomy, Queensland University of Technology Seminar Series. (2021). Beyond Honey: Improvements in beekeeping to optimize pollination and food security. Passcode: H8#83dz$

Cook, D. 2022. An examination of pollination and practice in Australian apiculture. PhD final seminar, Queensland University of Technology.
Cook 2021. Thermal impact of apiculture on the bee colony. Tocal college, NSW. October 2021. https://www.youtube.com/watch?v=CeEIRVyu-bg&ab_channel=NSWTocalCollege
Cook 2021. Apiculture practice and products: an inter-disciplinary industry project. Project overview, QUT Design for Change. August 2022. https://www.youtube.com/watch?v=5G2cv9Fa_E0

Prizes

Journal of Economic Entomology. Reader's Choice Awards for 2022. Was awarded to Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2021a). Thermal Impacts of Apicultural Practice and Products on the Honey Bee Colony. Journal of Economic Entomology, 114(2), 538-546. Presented as Cook et al (2022) Joint Annual Meeting of the Entomological Society of America (ESA), Entomological Society of Canada (ESC), and the Entomological Society of British Columbia (ESBC): Entomology as Inspiration: Insects through art, science, and culture. Vancouver, Canada.

Media Outputs

EntomologyToday.org. (2021). This Old Bee House: Study Deems Hive Boxes Drafty, Inefficient. https://entomologytoday.org/2021/04/16/honey-bee-hive-boxes-drafty-inefficient-temperature/
7 News Brisbane. (2021). Bee changes. https://twitter.com/7NewsBrisbane/status/1446766543761670147?s=20
Qut.edu.au. (2021). Sweet work: How better hive design can help keep bees warm. https://www.qut.edu.au/news?id=178727
Qut.edu.au (2021). Video: Keeping bees warm. https://www.youtube.com/watch?v=DUmnwin7vC8

Video

Cook, D. 2023. Cluster counter v1.0 software video: https://www.youtube.com/watch?v=k9dWufk_S24

Outcomes

This project addressed the demand from horticultural industries for evaluation of and dissemination of findings on hive standards, commercial pollination practices, and potential and actual use of sensing technology to determine colony health and, more specifically, hive strength in key horticultural industries (almond, avocado, cucurbits, blueberry). The aim of this critical evaluation is to provide information and increase confidence in pollination service practices and use of technology.

Significant disruptions and changes in pollination services occurred during the conduct of the project. Border closures and biosecurity measures imposed during the Covid pandemic and the incursion of varroa mite had significant impacts on pollination services and on this research. Sensing technology and adoption developed rapidly towards the end of the project, particularly with the 2023 partnership between Bee Hero technology and Monson's Honey and Pollination (the leading brokers to the Australian almond industry).

Table 2. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Development of industry best practices and quality assurance systems to improve European honey bee management and pollination, designed to fit current industry practice and align with the Honey Bee code of practice.	Outcome 1.1 KPI: Recommendations based on R&D available for best practice management of European honeybees.	**Industry participated in project process** through surveys, questionnaires and observation of practice,**and engaged with information disseminated** through industry presentations (10), public seminars and webinars (4), media outputs (4), training videos (1),	Industry participation is quantified and described in Appendix 1: Cook 2022, *An examination of pollination products and practice in Australian apiculture*. Engagement with information disseminated was determined from on-line metrics of citations, viewings, downloads. The presentation to industry at Tocal College NSW has been viewed over

		open-access peer-reviewed publications (5), open-access PhD thesis (1).	150 times since upload. Cook et al 2021b "Thermal Impacts of apiculture on the bee colony." In *New South Wales Apiarist Association Annual Conference*, 2021-05-20 - 2021-05-21, Tamworth, Australia, AUS. (open source) has been downloaded 118 times to date. Cook (2022) *An examination of pollination products and practice in Australian apiculture*. PhD thesis by Publication has been download 136 times since upload. Qut.edu.au (2021). Video: Keeping bees warm has had 269 views since upload. Cook et al 2021 "Thermal impacts of apicultural practice on the Honey Bee Colony" has been viewed 9356 times, has a score of 20 on Altmetrics (top 25% of all publications), and was awarded the Journal of Economic Entomology 'People's Choice' award 2022. Cook et al 2022 "Temperature sensing and honey bee colony strength" is rated as highly cited and has received approximately 4.74 times more citations than average.
Identify non-invasive colony evaluation technology that may effectively and clearly report colony strength against pollination service parameters	Outcome 1.1 KPI: Recommendations based on R&D available for best practice management of European honeybees.	Uptake and adoption of by growers, apiarists, commercial partners, manufacturers and other industry stakeholders	The adoption of sensing technology increased rapidly at the end of the project with the commercial partnership between Bee Hero technology and Monson's Honey and Pollination (the leading brokers to the Australian almond industry) in 2023.
Findings on standards and QA systems for colony strength for pollination services evaluation of non-invasive colony technology disseminated to target audiences.	Outcome 1.1 KPI: Recommendations based on R&D available for best practice management of European honeybees.	**information disseminated** through industry presentations (10), public seminars and webinars (4), media outputs (4), training videos (1), open-access peer-reviewed publications (5), open-access PhD thesis (1).	Links listed in this report

Monitoring and evaluation

Table 2 Key Evaluation Questions

Key Evaluation Question	Project performance	Continuous improvement

		opportunities
Cost/Benefit analysis and cost-effectiveness analysis. The project will engage expertise in cost/benefit analysis and will specifically evaluate the benefits and impacts on industry of both industry standards for hive strength in pollination, and sensing technology.	Existing hive standards based on FOB and audit practice based on cluster counts were evaluated through desktop review and experimental observation. The benefit and cost of sensing technology was evaluated by market scan of technology, review of fitness of parameters, and analysis of interviews with apiarists and orchardists.	Sensing technology and adoption developed rapidly through the project particularly with the 2023 partnership between Bee Hero technology and Monson's Honey and Pollination (the leading brokers to the Australian almond industry) and, to a lesser degree, through adoption of thermal imaging. Re-evaluation of the practice and application of hive standards and hive sensing technology would be of value.
Engagement analysis/ grower surveys and interviews. The project will specifically document, quantify and analyse industry practice and standards through interviews, surveys and observation of practice with industry (growers and apiarists), and with industry partners in commercial and technical development of hive sensing technology. It will evaluate the benefits and impacts on industry of industry standards for colony strength in pollination and sensing technology.	Interviews, surveys and observation were completed, analysed,and reported. Quantitative evaluation of sensing technology was conducted. Flaws in auditing practice and conversion of audit measures to pollination were identified, and addressed through experimental testing, development and dissemination of open-source hive standard software. Results disseminated through peer reviewed publication, open access video and webinars, industry seminars and conferences, and industry publications.	Software and corrections to conversion cluster counts to FOB could be developed as an industry app. Correction in conversion of cluster counts and application of hive auditing best practice (time of day) should be incorporated into the Crop Pollination Australia revision of BQUAL pollination hive standards and the planned.
Ethics review and monitoring. QUT will obtain internal ethics committee review and approval for interviews and surveys with growers as per standard QUT guidelines and requirements, work in which Prof Blackler has extensive experience. This will include specific processes on retaining data and identification of subjects.	Methods were submitted for QUT ethics review, approved, and periodically reviewed and modified throughout the duration of the project.	
Peer review. Project data and outputs will be made available in the public domain through publication in peer reviewed journals, research conferences and industry meetings, and in reports to industry.	Results were disseminated through peer reviewed publication, open access video and webinars, industry seminars and conferences, and industry publications.	Final publications are in press or in advanced stages of completion for submission of manuscripts. An article for the almond industry periodical 'In a Nutshell' is in preparation
Project review. A Project Reference Group (PRG) will be set up that includes apiarists, growers and Hort Innovation representation, and will review the project every six months, in face to-face meetings (in Brisbane), and by remote connection (Zoom, telephone) in the intervening six months.	A project review group was set up and operated largely through Zoom due to COVID restrictions. A full project review was completed at end of year 2.	Project review was significantly affected by biosecurity issues (COVID, varroa mite incursion) and a final project review was not conducted.

Recommendations

Contracting in almond pollination encourages better apicultural practices through use of hive standards and audits, whereas smaller-scale crop pollination (avocado, blueberry, apple, cucurbits, macadamia) may expose both farmers and apiarists to a measure of legal and financial risk in the form of non-optimal pollination, bee colony chemical exposure and the spread of disease. Wider use of contracts with stipulated standards would clarify expectations and provide a benchmark for apiarists.

The design of Langstroth hives (boxes) developed for honey harvesting is clearly not fit for purpose in pollination services. Apiarists routinely modify honey hives to reduce weight (half-depth boxes) and fit of frames (9 frames of comb in a 10 frame box). Since most hives are used for honey production when not in use for pollination, these modification can lead to non-standard hives in pollination services that impact on auditing and colony strength estimations. no Australian Standards (AS) or ISO standards exist for beehives. Further work on materials to reduce weight and increase size of the hive to fit ten frames for pollination (increasing the standard FOB to 9) is recommended. We suggest the creation of a hive standard, including road mapping of the beehive product ecosystem with ergonomics, migratory transport and usability in mind, would lead to improved apicultural products and practices, and generate efficiencies within the industry.

The concepts of pollen or nectar driven foraging behaviour in different crops has not been explored and appear to be poorly understood in the Australian pollination services. Further work on nutritional drivers of foraging behaviour and the use of, for example feeding strategies to stimulate egg laying, and timing of supplemental feeding to drive increased foraging may result in bee colonies 'tuned' to particular crops, and thus to enhanced and more efficient pollination services, requiring fewer hives.

Sensing data clearly demonstrated the significant impact of migratory pollination on hive homeostasis and resulting stress on bees. The lack of data on hive failure shortly after transport and on the longer-term impacts of transportation (often multiple trips) on bees suggests the need for a longitudinal study of effects on colony health. A program of long term (2-3 years) continuous hive tracking and periodic strength measurement may identify 'pinch points' that can be addressed to reduce impacts of migratory apiculture on bees.

Finally, some sensing technology has demonstrated a capacity to overcome shortcomings in application of hive standards. Despite initial reticence by practitioners, the use of hive sensing technology combined with machine learning and data services (such as Bee Hero) will accelerate in coming years as costs decrease and access to internet services increases even in remote areas. The establishment of more reliable technology and benchmark pricing will enable a more complete cost-benefit comparison of the various technologies in the pollination or orchard crops.

Refereed scientific publications

Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2021). Thermal Impacts of Apicultural Practice and Products on the Honey Bee Colony. Journal of Economic Entomology, 114(2), 538-546. https://academic.oup.com/jee/article/114/2/538/6168215

Cook, D., Tarlinton, B., McGree, J. M., Blackler, A., & Hauxwell, C. (2022). Temperature Sensing and Honey Bee Colony Strength. Journal of Economic Entomology. https://doi.org/10.1093/jee/toac034

Cook, D., Hauxwell, C. (2024). Providing rigor in bee colony strength auditing methods. Journal of Economic Entomology. *In Press.*

Cook, D., Tarlinton, B., McGree, J. M., Blackler, A., & Hauxwell, C. (2024b). Temporal bias in the cluster count bee colony audit method. *In preparation*

Cook, D., Sepahpour, G., Blackler, A., & Hauxwell, C. (2021). Perspectives on Australian Pollination. *In preparation*

Thesis

Cook, Daniel L. (2022a) An examination of pollination products and practice in Australian apiculture. PhD by Publication, Queensland University of Technology. https://eprints.qut.edu.au

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Clarke and Le Feuvre (2023). Final report: Australian pollination service statistics (HA21005). Published and distributed by: Hort Innovation. Final report

Cook, D., Blackler, A., McGree, J., & Hauxwell, C. (2021a). Thermal Impacts of Apicultural Practice and Products on the Honey Bee Colony. Journal of Economic Entomology, 114(2), 538-546. https://doi.org/10.1093/jee/toab023

Cook, D., Blackler, A., & Hauxwell, C. (2021b). Perspectives on Australian Pollination. http://dx.doi.org/10.2139/ssrn.3964582

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Nasr, M. E., Thorp, R. W., Tyler, T. L., & Briggs, D. L. (1990). Estimating honey bee (Hymenoptera: Apidae) colony strength by a simple method: measuring cluster size. Journal of Economic Entomology, 83(3), 748-754. https://doi.org/10.1093/jee/83.3.748
Oliver, R. (2018). Determining The Relative Value of Hives for Almond Pollination. American Bee Journal, 158(10), 1125. https://bluetoad.com/publication/?m=5417&i=528323&p=52&ver=html5
Stalidzans, E., & Berzonis, A. (2013). Temperature changes above the upper hive body reveal the annual development periods of honey bee colonies. Computers and Electronics in Agriculture, 90, 1–6. http://doi.org/10.1016/j.compag.2012.10.003
Zacepins, A., Kviesis, A., Stalidzans, E., Liepniece, M., & Meitalovs, J. (2016). Remote detection of the swarming of honey bee colonies by single-point temperature monitoring. Biosystems Engineering, 148, 76–80. http://doi.org/10.1016/j.biosystemseng.2016.05.012

Intellectual property

No project IP or commercialisation to report

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Appendices

Appendix 1: An examination of pollination products and practice in Australian apiculture.

Detailed background, methods and conclusions are listed in the on-line, open-access PhD thesis by Dr. Daniel Cook (2022). This PhD was funded by QUT and Hort Innovation as part of PH17001.

Cook, Daniel L. (2022) An examination of pollination products and practice in Australian apiculture. PhD by Publication, Queensland University of Technology. https://eprints.qut.edu.au

Appendix 2: Report of the desktop review of pollination standards.

Review: Hive Standards and factors affecting pollination potential of honey bee colonies

Cutting B., Gee M., Evans L., Hauxwell C.

Executive Summary

We undertook a review of available standards for honey bee hives used for pollination, with particular focus on crops in Australia and New Zealand. These standards will serve as a baseline during ongoing development of new tools for monitoring and manipulating colonies used for pollination service provision. The literature review primarily used systematic search methods to locate published articles in scientific literature and agricultural databases. This was subsequently expanded using other available resources, expert knowledge, and consultation with stakeholders.

The most standardised metric for a 'minimum standard' for hives used for general crop pollination is that each hive should contain at least 8 full Langstroth frames (or equivalent area) covered with adult bees. There is variation in this standard, notably for kiwifruit pollination in New Zealand, where 12 frames of bees represents the minimum standard.

In addition to frames of bees, most guidelines include minimal requirements for a certain area covered with developing brood of various ages (generally 4 frames, with 25% uncapped). Additional requirements call for provision of vigorous egg-laying queens, disease and parasite-free colonies, supplemental food resources, and space within the hive for colony expansion are also frequently included.

Under most conditions, pollination activity is closely related to colony strength (bees and brood) and total pollination service provision is a function of hive strength and number of hives provided. Therefore, it is recommended that growers and beekeepers enter into pollination contracts which include both colony numbers and strength, to ensure that pollination needs are met. Rental prices should then be adjusted according to colony strength. The general pollination standards serve as an industry-relevant starting point for calibrating hive monitoring tools and management practices, which can then be fine-tuned to meet the needs of particular cropping systems and regions.

Introduction

Honey bee colonies used for crop pollination are subject to numerous conditions (bee numbers, resource availability, disease pressure), which can impact their health and behaviour and consequently their efficiency in delivering a pollination service. By monitoring and manipulating hives, beekeepers can ensure that colonies are optimised for crop pollination. New hive monitoring technologies have the potential to allow real-time assessment of pollination readiness with lower input cost and reduced disruption to hives. These tools should be developed using current understanding of best practice for pollination and understood industry standards for pollination service provision.

We have reviewed the relevant available literature on managing hives for crop pollination, with a particular focus on guidelines for Australia and New Zealand. While much of the scientific literature on hive efficiency is most appropriately applied in a specific context (i.e. region, crop, growing system), generalised parameters for what constitutes a 'pollination unit' are available and partially consistent across regions and industries.

Methodology

A systematic search of the literature was conducted using the CABI (Cab Abstracts® and Global Health®) database using the following search terms: Topic = ((apiar* or hive*) and pollinat* and (strength* or strong or health or forecast* or timing or densit* or manag* or standard* or practic* or "remote sens*")). This search returned 955 records, of which 112 were selected based on having relevant titles. The same search terms were used with the Proquest database (NOFT), returning 535 records of which 50 were selected (9 were duplicates). The 153 potentially relevant articles were further evaluated based on the content of the abstract. Very few articles contained direct reference to hive strength for pollination, and only 13 summarised empirical research relevant to hive strength (See Appendix 1 for list). In addition to the systematic search, additional resources were located using prior knowledge, google search, references in surveyed literature and interaction with pollination stakeholders. Relevant information from these resources is summarised below.

Pollination Hive Standards

Numerous publications have made reference to prescribed standards for hive condition for pollination service provision (Table 1). The published standards are variable, however in most situations the authors recommend a minimum hive strength of 8 full frames of adult bees (or equivalent) and 4 frames of brood of various ages (Phillips, 2014; Traynor, 2010). Hive standards are notably higher in kiwifruit in New Zealand, a high-value crop which is highly dependent on pollination, and is not a preferred forage resource for bees. In Kiwifruit, minimal hive standards are 12 frames of bees per hive (Goodwin, 2000, 2012).

In addition to frames of adult bees and brood, most documents directly referencing hive standards also mention some or all of the following conditions which should be met by honey bee colonies used for pollination:

- Must contain a young, healthy, laying (not caged) queen (Thorp et al., 1974)
- Should be relatively disease/parasite free (K S Delaplane, Mayer, & Mayer, 2000; Matheson, 1991; D Somerville, Frost, & Laffan, 2018)
- Should contain uncapped brood (generally 25% of total brood area) (Matheson, 1991)
- Need sufficient honey reserves to last pollination period (2 frames minimum)(Goodwin, 2012; Doug Somerville & Frost, 2018)
- Additionally, some authors comment that brood frames should be present in the bottom box, near to the hive entrance to stimulate pollen foraging (Free, 1979; Matheson, 1988, 1991)
- Hives should contain drawn out, empty comb in which queens can lay eggs and expand the colony (Goodwin, 2012; Tew & Caron, 1988).

Generally, these standards are to ensure that colonies contain a large foraging force that is actively collecting pollen. It is assumed that pollen foragers will be more efficient pollinators than nectar foragers due to increased contact with flower reproductive parts (Free, 1979), though this will not be true in all systems, for example, hybrid crops with male-sterile lines may present an exception. Hive history and health has a strong impact on foraging force and disease can limit the number and activity of foragers in a hive (Alger, Burnham, Lamas, Brody, & Richardson, 2018). In strong hives, pollen foraging is stimulated by the presence of eggs and brood in the colony (Free, 1979). For flowers that produce very little nectar (e.g. kiwifruit, (Goodwin, 2012)) sucrose or honey is often provided to bees to increase pollen foraging and therefore pollination (Fewell & Winston, 1992).

While hive standards are based on the above understanding of honey bee behaviour and crop floral biology, the specific standards are based on little empirical research.

Sheesley & Poduska (1970) analysed almond pollen collection records from 256 honey bee colonies of varying foraging strength – between 1 and 18 frames of adult bees. They found that larger colonies collected increasing amounts of pollen and were presumed to be more efficient pollinators than small colonies. Hives with fewer than 3 frames of bees collected no pollen. The conclusions of these studies were that number of hives needs to be adjusted to account for colony strength. These have been broadly interpreted as a need for pollination hives to contain 8 frames of bees or more, the basis of the general pollination standard, and provide useful clarity to the economics of hive rental, as well as a functional definition of 'normal pollination conditions' useful to agronomists and researchers.

While some industry specific standards have been adopted (see 'case studies' below, and Appendix 1 for full list), other published standards have included general adaptations for 'orchard-grade' versus 'field-grade' pollination units, as well as providing provision for 'B-grade hives of each which fail to meet standards, but do so in a limited way (Roubik, 1995). As above, these standards were developed to facilitate beekeeper-grower interactions, rather than being formed from in-depth understanding of pollination needs. The lowered strength standards for 'orchard-grade' units reflects not a reduced pollination requirement in these environments, but rather a practical limitation to colony size during early Spring when many fruit trees are in flower (versus arable crops in mid-summer, after springtime recovery of hives from overwintering).

Table 1: Select publications referencing hive strength standards for different regions and crops.

Reference	Region	Bees (frames)	Brood (frames)	Crop
(Matheson, 1988)	New Zealand	12	4	kiwifruit
(Jones, 1992)	Australia	NA	6.8 (6000 cm^2)	lucerne
(K S Delaplane et al., 2000)	USA	6-10	4-6	general
(Keogh, Robinson, & Mullins, 2010)	Australia	8-10	2.5-3.5	general
(Goodwin, 2012)	New Zealand	12	4	kiwifruit
(Goodman, 2014)	Australia	8-10	2-4	almonds
(Goodman, 2014)	Australia	8+	6	stone fruit
(D Somerville et al., 2018)	USA	8	4	almonds
(D Somerville et al., 2018)	New Zealand	12	4.2	kiwifruit
(D Somerville et al., 2018)	Canada	8	4	blueberries

Enforcement of standards

Two US states have historical hive standards which were written into state law (Sagili, R.R.; Burgett, n.d.)(see Appendix 2). Washington state required hives to have a minimum of 6 frames with 4 frames of adult bees. Oregon required hives to contain 3.5 frames of brood and 10 frames of comb, as well as being free from disease and have an actively laying queen to qualify as an 'A Grade' field pollination hive. These standards are not available at present via the Oregon or Washington state online archives, and may no longer be in effect. ("Oregon Administrative Rules, Chapter 603," n.d.; "Washington Department of Agriculture Apiary regulations," n.d.)

Elsewhere, enforcement of hive standards is generally undertaken by pollination stakeholders. Some beekeeping associations enforce their own hive standards (e.g. "Nova Scotia Beekeepers Association - Pollination Standard," n.d.) and certain industry bodies administer standards and provide resources for auditing hives. In most cases, adherence to hive standards depends on self-reporting by beekeepers. However, many beekeepers do not follow an inspection checklist or keep close records of hive strength (Cazier, 2018) and many hives do not meet standards (Murray & Eaton, 1995). Generally, provisions for hive audits should be agreed upon within a pollination contract, and either beekeepers or growers can request an internal or third-party audit if they have concerns about hive status (Goodrich & Goodhue, 2016).

Under the Australian Biosecurity Code of Practice, apiary sites must be inspected twice per year (no fewer than 4 months apart). This provides the only legislative requirement in Australia for apiarists to directly inspect and record the status of hives. These regulations are primarily developed for bee-biosecurity rather than pollination, but may nonetheless have some positive effects on increasing accountability regarding strength of hives used for pollination. Pest and disease status are required to be recorded, along with the 'general hive strength' and 'overall strength of the hives within an apiary' (The Australian Honey Bee Industry Biosecurity Code of Practice, 2016). Bee Biosecurity Officers must be allowed access to perform audits if requested. The Australian B-Qual Handbook has a section on pollination standards, which references the Biosecurity Code of Practice and recommends the signing of pollination agreements, with the 'strength of hives agreed to before placement'("B-Qual Accreditation Standards," 2019).

Case Studies

Almonds

Some early published pollination hive standards resulted from requests from almond and alfalfa seed producers for standards for hive rental purposes. Representative beekeepers and the University of California extension office proposed minimum standards for these industries which were expected to be serviceable based on market demand and timing of crop flowering – these included four frames of bees and an active laying queen for almond pollination ("Miminum standards for hives rented for pollination," 1969). Rather than incorporating empirical research on pollination efficacy, these guidelines were based on achievable average hive strength for early flowering crops. Essentially, this arbitrarily defined a pollination unit to set a baseline for contract negotiations between apiarists and growers.

Subsequent research evaluated the pollination efficacy of hives of varying strength (1-18 frames covered with bees) for almond pollination (Sheesley & Poduska, 1970). This study demonstrated that stronger hives collected more almond pollen (a proxy for flower visitation and therefore pollination), and advocated for adoption of a scalable hive rental pricing structure based on hive strength. Subsequent references to this study have interpreted conclusions as recommending 8 frames of bees as a standard, however a precise recommendation was not made, rather, it is recommended that stocking rates and hive rental prices are calculated according to hive strength (Oliver, 2018). Eight frames of bees is generally accepted as a minimum standard for pollination units in almonds in the US (more than 45% of growers report to adhering to this guideline (Goodrich & Goodhue, 2016).

Goodrich and Goodhue (2016) report that colony strength audits can typically be initiated by either the grower or beekeeper, and are carried out by a third party. Incentive-based contracts are recommended, where a base price is agreed upon between the apiarist and grower, and prices are adjusted based on whether average hive strengths in representative audits fall below or above the 8-frame standard (Goodrich & Goodhue, 2016).

Kiwifruit

Kiwifruit flowers do not produce nectar and much of the pollen produced is of low nutritional value to honey bees, which may learn to forage on other, more rewarding flowers near the crop (Goodwin, 2000). Many kiwifruit varieties are also heavily dependent on cross pollination for adequate fruit set and development. Consequently, pollination by managed honey bees requires a high stocking rate of strongly foraging colonies (Goodwin, 2000).

Most major Kiwifruit producers in New Zealand (Zespri, Eastpack, Trevelyan's) have adopted a basic standard of 12 frames of bees in a pollination unit and adhere to other standard guidelines (presented in Table 1, Appendix 1). These standards have also been adopted by the Kiwifruit Pollination Association (see Appendix 4). Provisions for audits, if required, are generally contained with pollination contracts. Several private commercial entities provide third-party auditing and certification services in New Zealand (AsureQuality, n.d.), some larger producers may require a representative audit of provided pollination hives as standard practice. Some beekeepers providing pollination services engage auditors themselves as a way of assuring their grower-clients of hive rental value (Foster, 2010).

Australian Industries

Several large-scale producers in Australia (berries, avocados) have indicated that they have implemented hive standards for pollination, or are in the process of developing standards. While recommended standards are well circulated amongst beekeeper and grower targeted resources in Australia, generally these provisions are only present for industries which are strongly dependent on honey bee pollination, and face challenges to hive supply (i.e. covered environments, high hive demand during flowering periods) or in locations where full pollination can be difficult to achieve (i.e. locations with competing floral resources).

Special Considerations

In some environments, it is likely that hive standards will need to be modified to support bee health and optimal pollination service provision. As stated previously, pollen gathering bees are thought to be more efficient crop pollinators, however, some hybrid crops (i.e. carrot seed, watermelons) produce little to no pollen on pistillate (fruiting) flowers. In these cases it could be expected that nectar gathering bees will visit fruiting flowers more often and contribute substantially to pollination.

Protected cropping environments present special challenges to beekeeping and pollination (Evans et al., 2019), and likely require separate hive standards. There is some suggestion that smaller colonies may outperform larger ones in covered environments (Pinzauti, 1994), and several designs for small pollination units have been tested (Keasar et al., 2007; Manning, 2002).

Next Steps

The advent and uptake of new hive sensing technologies and data analysis tools brings opportunity to better understand the numerous factors with potential to affect per-hive pollination efficiency, and to do so in a cost and time-effective way (Avni et al., 2015; Bencsik et al., 2011; Edwards-Murphy, Popovici, John, Magno, & Pádraig, 2016). While the pollination unit standards presented here are fairly 'broad strokes' approaches to visual assessment, these developing technologies will allow a new type of assessment based on large multivariate data sets. The European Food Safety Authority has published guidelines for detailed hive assessments incorporating colony attributes, external drivers, and colony outputs (EFSA AHAW Panel (EFSA panel on Animal Health and Welfare), 2016). Incorporating elements of this system into data collection is recommended to facilitate contribution to global data sets on bee health. Additional methodology for hive assessments for research purposes is available in Keith S Delaplane, van der Steen, & Guzman-Novoa (2013).

Summary

While hive standards have been implemented by some pollination dependent industries in Australia and New Zealand, generally implementation and enforcement is sporadic. Existing standards are useful for providing a baseline for pollination research, and for discussing the economic forces affecting hive availability and rental pricing. Generally, standards are guided by an understanding of bee biology and a need to define a minimal acceptable foraging force within a colony used for pollination. However, there is very little empirical research into optimal hive conditions for providing pollination services. There exists a need for further research into hive conditions for optimal pollination.

A barrier to understanding of hive requirements is that overall pollination service is affected by multiple factors – not only hive strength but by factors external to the hive as well. Likewise, the provision of pollination services is a function of stocking rate and the foraging strength of hives introduced. Pollination requirements are impacted by environment and landscape, as well as crop biology.

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Appendix 3: Practical Value of Beehive Remote Monitoring Equipment

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Background

When inspecting a honey bee colony beekeepers will typically visually assess (depending on the season):

- Disease status
- Queen status
- Swarm status
- Food availability
- Space availability
- Colony strength

These features are assessed, because in some instances they are legally required but more frequently, because variations may have commercial implications and because there are remedial actions available in real time to beekeepers as summarised in Table 1.

Although regular colony inspections are both a commercially prudent and, at times, essential part of successful beekeeping they can also be expensive, time consuming and inconvenient. This is particularly the case in Australia when a beekeeping business may be operating over considerable distances

Opportunity for Remote Monitoring

Remote monitoring of honey bee colonies is an obvious way to streamline the inspection processes of commercial beekeeping and many different remote sensor packages designed to monitor honey bee colonies are commercially available (Cook 2022). Various combinations of colony attributes are measured by these devices which fall into seven broad categories – temperature, humidity, weight, bee counter (typically at entrance), CO2 levels, vibration/acceleration and general acoustics and video. We will review each of these categories considering both technical challenges, alignment with relevant physiology of the colony (currently understood), and commercial applicability.

Temperature

The major logistical challenge when measuring temperature in a bee hive is probe location. In the centre of the brood nest is a logical position which bees maintain at 32°C - 35°C for healthy brood development. The challenge is that the brood nest location naturally migrates around the hive over the course of a year and thus the temperature measuring probe will also need to be manually relocated.

Providing the probe is consistently taking temperature measurements at the centre of the brood nest, prolonged, extreme changes in temperature (outside the 32°C - 35°C range) will have fitness implications for the colony and can indicate a level of colony dysfunction, including colony death or queen loss.

Remedial actions for a colony that persist but fluctuate between being too hot or too cold include using hiveware that is insulated, with ventilation and it is our conclusion that these remedial actions are likely to be done as part of scheduled work rather than as something done immediately as part of "real time" monitoring.

Applicability: Currently low. There are technical challenges of achieving consistent and reliable temperature monitoring, minimal colony status changes that are likely to be identified, and limited commercially relevant remedial actions from this monitoring approach.

Future Possibilities If temperature is demonstrated to be clearly linked to queen failure or queenlessness (i.e. unexpected reduction in brood production) there would situations where feedback from temperature monitors could inform beekeeper decision making in real time (i.e. visiting an apiary to replace defunct colonies to provide pollination services or collect a honey crop). Furthermore, instances of slight increases in brood nest temperature have been demonstrated in controlled studies in response to *Nosema* sp. infection. However the precision and distribution of monitors throughout the brood nest required to detect this is degree of change is beyond the scope of current commercial devices available to beekeepers.

Table 1. Overview of beekeeping inspection practices and the relative costs of those practices (cost of performing inspections and/or the productivity loss if inspections are not conducted and therefore identified problems are not remedied).

	METHOD	BEEKEEPER COST OF MANAGEMENT (TIME)	REMEDIAL ACTION	BEEKEEPER COST OF NO MANAGEMENT	ORCHARDIST COST
DISEASE STATUS	Visual Inspection of brood. Smell.	Medium	Containment, treatment, re-queening	5-40% loss in honey (Productivity loss and colony loss)	-
QUEEN STATUS	Visual Inspection of brood or queen	Low	Re-queening	Low-Medium (Colony strength and failure)	-
SWARM STATUS	Visual Inspection for swarm cells	Medium (spring/summer)	Swarm cell removal	10-40% honey crop (Loss of workforce + honey with swarm)	-
FOOD AVAILABILITY	Visual inspection of stored food. Hive weight	Low	Feeding	Low (Colony starvation)	-
SPACE AVAILABILITY	Visual inspection of available comb. Hive Weight	Medium	Additional boxes provided. Hive re-organisation	Medium-High (colony unable to expand and store honey, spring summer)	-
COLONY STRENGTH	Visual inspection.	Low	Brood and bees reallocation.	Low-Medium (Suboptimal colonies deployed for pollination and honey collection)	Low (contract cost of auditors)

Humidity

A honey bee colony actively manages humidity in the brood nest and honey supers. The inability of a colony to modify the humidity of the hive impacts brood viability, honey production and disease levels (e.g. Nosema sp. and chalkbrood). Beekeepers are able to facilitate colony humidity control by providing hiveware that allows for airflow e.g. vented floorboards and/or hive mats. When considering regular monitoring of humidity we are not aware of any data to describe “optimal humidity” nor what a beekeeper is able to do to provide that optimal humidity beyond the hive infrastructure. Changes to hive infrastructure represent an overhead investment that is best approached as part of scheduled beekeeping rather than a real time response to remote sensor feedback.

Applicability: Currently low. Humidity is relevant to honey bee colony health and productivity but the links between real-time changes in humidity and colony function/productivity are unknown. Beekeepers can do little to achieve optimal humidity beyond modifying hive infrastructure to allow the colony to adjust humidity which represents a systematic change to a beekeeping operation rather than real time beekeeping decisions informed by real time sensor monitoring.

Weight

Increases in hive weight indicates colony strength, and resource (primarily nectar) collection. If this information is fed back to the beekeeper in real time there is the opportunity for the beekeeper to put additional honey boxes on the hive and increase the honey storage capacity of the beehive, thus maximising honey crop. In practice, most beekeepers already have the inventory and systems to provide sufficient honey storage as part of routine activities making real time monitoring somewhat obsolete. Furthermore, this aspect of colony management (adding honey boxes for maximum honey production) is less relevant to honey bee colonies providing pollination services.

Similarly, decreases in hive weight indicates a colony is decreasing in size or depleting stored honey and when a particular lower threshold of weight (i.e. stored food) is reached this can trigger the beekeeper to provide supplementary feeding avoiding colony death by starvation. Again, in practice most beekeepers have systems and infrastructure to provide pre-emptive scheduled supplementary feeding of sugar syrup to minimise colony death from starvation.

In spring there are often noticeable fluctuations in hive weight as different floral crops flower and honey bee colonies flow. This may not always be apparent to beekeepers but is “normal” and doesn’t usually require an intervention (and the intervention of sugar syrup feeding may be expensive and unhelpful to the colony). Detailed real-time feedback on colony weight without thorough understanding between those immediate values and the long term productivity of that colony are likely add some degree of anxiety and possibly encourage unnecessary, expensive, and/or unhelpful interventions.

Applicability: Currently moderately low. Hive weight does indicate status of stored food in a hive and can be used to inform management decisions (as it sometimes is as part of general hive assessment). However, the two remedial actions – providing additional boxes for honey collection or providing supplementary sugar syrup feeding – is usually already done pre-emptively by commercial beekeepers making the monitoring somewhat obsolete when trying to incorporate with existing beekeeping practices.

Of all the metrics assessed by commercially available hive sensors, weight is one of the most intuitive to imagine value for orchardists. The average weight of colonies in the orchard could replace the need for auditors to confirm colony strengths of contracted pollination colonies. However, this is also a simple metric to “cheat” by adding weight to colonies and therefore would not completely replace the need for visual inspection of colonies. Perhaps if paired with video monitoring and/or bee counts could begin to work towards fully automated auditing of pollination colonies for orchardists (see the individual discussions of the present limitations of bee counts and video monitors).

Bee Counter

This technology requires tight beehive equipment with no “alternative entrances” (gaps between boxes etc.) to be effective. It is also noted that achieving and maintaining calibration of counter information with actual bee activity has proved challenging. Bee activity at the hive entrance will be related to the strength and status of the colony. However, we are not aware of meta-datasets demonstrating a threshold for optimal bee activity for pollination or honey collection requirements.

Therefore, it is not clear how bee activity can inform decision making (for the beekeeper or orchardist) other than extremely low levels indicating colony failure. It is also noted that temperature, weather and food availability all impact bee activity at the hive entrances masking signals of colony strength and status. Detailed real- time feedback on bee counts at the entrance without thorough understanding between those immediate values and the pollination service or the honey production of that colony are likely to generate unnecessary anxiety and potentially create conflict between beekeepers and orchardists over the value of the pollination service being provided by the contracted colonies.

Applicability: Currently low. This is a promising area of monitoring but we are not aware of verified systems that are able to provide an absolute measure of optimal pollination or honey collection capacity.

CO2

Like all animals honey bees produce CO_2 through respiration. Furthermore, as a superorganism, the colony also has distinct periods of “inhalation” where O_2-rich air is brought into the hive and “exhalation” where CO_2-rich air is removed from the hive through the fanning activity of workers at the hive entrance. There are an average of 10 cycles of inhalation and exhalation in a minute. Presumably, in-hive CO2 monitors would detect these cyclical variations in colony-level respiration.

Applicability: Currently low. We are not aware of how CO2 production relates to colony productivity in pollination and/or honey production and thus how detected variation in CO2 production could be used to inform management decisions.

Acoustics & Video

This is an interesting space with potential. Video monitoring of a honey bee colony will not be able to substitute the visual inspections underpinning conventional beekeeping inspections (Table 1) because the video camera is in a fixed position while beekeeper inspections are typically highly mobile shifting around frames etc. However, we are aware of some interesting work around the use of machine learning from video footage to assess attributes like Varroa infestation rates – particularly relevant for sentinel monitoring for a potential Australian Varroa incursion.

The acoustics (buzzing) of a colony is known to vary with some colony conditions: experienced beekeepers will often predict queenlessness based on the modified behaviour and resulting sound of a queenless colony when the hive is opened for inspection. The challenge is aligning the type of colony level buzz with potential issues. We are aware of ongoing research in this field. However, there are not yet clear indications for practical application.

Applicability: Currently low. The science support of the remotely monitored metric is still developing. Both acoustics and video, supported by machine learning, are exciting areas to follow.

Vibration/Acceleration

During transit between apiary sites or after an acute accident (i.e. the hive is knocked over by a work vehicle, falling tree, stock, etc.), honey bee colonies experience vibration/acceleration that can be detected by remote sensors. These sensors can offer real-time feedback to beekeepers in the event of colony theft or accidental disturbance that may require immediate attention to reassemble a colony that has been knocked over. The utility of this reassurance will be strongly dependent on the beekeeper’s perceived risk to their colonies and other potential associated cost savings (i.e. reduced premiums for operation insurance).

Applicability: Currently moderate. While there are identifiable conditions that can be detected via Vibration/Acceleration, those are rare occurrences and may not justify the acquisition of an individual monitoring device for every colony in a beekeeper operation.

Summary and Directions

As superorganisms, honey bee colonies function as complex ecosystems – measurable attributes vary both in response to and independently of external factors. As such, clearly connecting these measurements to colony condition still represents a major research challenge. However, improvements in electronics (sensor and power supply miniaturisation, improved efficiency and sensitivity, and lower cost) has advanced the state of the field to where it is practicable to deploy measuring devices in greater numbers and at higher density. Paired with advanced data analysis techniques (machine learning) these tools are likely to lead to increased understanding of within-hive dynamics.

Because of the large variation which is normal between colonies, further advances in the field are likely to be driven by large-scale replication, rather than by enhanced measurement accuracy. When the hive variables above are more clearly linked with biological indicators, the commercial challenge will become incorporation of these into devices which clearly bring value beyond conventional visual hive inspections.

The cost of adding sensing devices must compare favourably to costs of simply running additional hives to compensate for colony death or poor production. This economic assessment also needs to factor in additional costs of loss of sensing hiveware due to fire, theft, degradation, or obsolescence. The costs and benefits will vary depending on the objectives and management style deployed by a beekeeper, and the location of their operation. Apiarists are recommended to apply the criteria outlined in Table 1 using values estimated from their own business when assessing the potential value of new technologies.

Deployment of remote monitoring equipment for honey production and pollination provision involves another layer of complexity, as these are heavily influenced by ecology outside of the hive. Trees that are targeted for honey crops can be inconsistent in flower and nectar production, both between regions and between years. Both honey collection and pollination provision are highly dependent on weather. Finally, the basic pollination requirements and hive stocking rates of most crops is not well understood. The number of pollen grains required for fertilisation and fruit production can vary greatly between cultivars, and so the frequency of bee visits required may vary accordingly. While some pollination-dependent industries do have hive standards for pollination, these are based on very little experimental data, and the optimum colony conditions for providing efficient pollination service are not fully understood.

Research is currently underway on technologies for bloom forecasting for certain trees, improved understanding of pollination requirements of crops, and optimal hive conditions for honey collection and pollination provision. The greatest value of hive-sensing technologies will likely come when these are deployed in parallel with advanced understanding in these related fields. This underscores the importance of continuing to investigate fundamental biology alongside developing technologies.