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Opportunities for Precision Feed in Apiculture for Managing the Efficacy of Feed and Medicine

John Michael Russo

***Abstract*—**Honeybees are important to our food system and continue to suffer from high rates of colony loss. Precision feed has brought many benefits to livestock cultivation and these should transfer to apiculture. However, apiculture has unique challenges. The objective of this research is to understand how principles of precision agriculture, applied to apiculture and feed specifically, might effectively improve state-of-the-art cultivation. The methodology surveys apicultural practice to build a model for assessment. First, a review of apicultural motivators is made. Feed method is then evaluated. Finally, precision feed methods are examined as accelerants with potential to advance the effectiveness of feed practice. Six important motivators emerge: colony loss, disease, climate change, site variance, operational costs, and competition. Feed practice itself is used to compensate for environmental variables. The research finds that the current state-of-the-art in apiculture feed focuses on critical challenges in the management of feed schedules which satisfy requirements of the bees, preserve potency, optimize environmental variables, and manage costs. Many of the challenges are most acute when feed is used to dispense medication. Technology such as RNA treatments have even more rigorous demands. Precision feed solutions focus on strategies which accommodate specific needs of individual livestock. A major component is data; they integrate precise data with methods that respond to individual needs. There is enormous opportunity for precision feed to improve apiculture through the integration of precision data with policies to translate data into optimized action in the apiary, particularly through automation.

***Keywords*—**Apiculture, precision apiculture, RNA varroa treatment, honeybee feed applications.

I. Introduction

FEED practice in apiculture is not new. It is a significant and useful tool for beekeepers. It is highly versatile and can be adapted to a number of situations to improve apiary performance, treat disease, and reduce colony loss. Precision feed is also not new in agriculture. Dairy industry reports describe precision feed as: "the continual process of providing adequate, not excess, nutrients to the animal and deriving a majority of nutrients from homegrown feeds through the integration of feeding and forage management for the purpose of maintaining environmental and economic sustainability" [1]. Intuitively, these principles would apply just as well to apiculture. However, the application of precision feed to apiculture, or precision beekeeping in general, is relatively less advanced. An internet search of precision apiculture for research done in 2018 yielded few results. Zacepins et al. offer the following definition: "Precision Apiculture or Precision Beekeeping is an apiary management strategy based on the monitoring of individual bee colonies to minimize resource consumption and maximize the productivity of bees" [2]. The primary individual unit in precision apiculture is typically the colony, or hive, rather than the individual bees themselves. Any apicultural enterprise would likely already have an established cultivation regimen. Any practical application of precision feed would need to adapt these specific apicultural feed practices to the individual needs of each managed colony at any given time. It is therefore important to understand these practices and how they might evolve. This is the method used to identify the opportunity.

It is likely that most large apiaries have not yet realized the comprehensive benefits of precision feed methods. There is twofold evidence of this. First, exceedingly little information on precision feed practice as applied to beekeeping exists. Most information on precision feed is focused on larger livestock, primarily dairy and cattle. What's more, the products available for these other industries, in large, will not readily support apiculture. The methods are just too different. There are numerous apiculture specific products available for dispensing feed itself and using feed for the administration of medications. However, the extent to which individual hive data are driving the selections and distributions of these products would define the extent to which a management strategy implements precision feed techniques. In this regard, there are a number of practical challenges to the economical collection and use of data. Therefore, data are a particular area of interest in this analysis.

General strategies and techniques of precision feed used successfully in other industries should apply with similar benefit to apiculture if they can be adapted to the idiosyncrasies of beekeeping. This creates an opportunity to explore how feed practice might develop in the apiary with benefits comparable to these other industries. Much is known and new studies continue to identify new ways feed can benefit honeybees. Efficiently integrating this expanding knowledge into practice has the potential to dramatically change apiculture and its relationship to science. Yet, to be successful, many complex issues must be considered. Even for beekeepers with a relatively good knowledge of feed strategy, reducing them to practice is not always straight forward. Every apiary site has its own unique performance. Every colony has its own performance requirements. And every colony responds to feed strategies a little bit differently. This complexity, the very source of difficulty in real practice, is itself an opportunity for a precision feed approach. Effective methods should be able to track

John Michael Russo is with Carmel Lavender Farms, Tenchiro LLC, United States (e-mail: john@tenchiro.com).

specific metrics at both the individual site and colony level and utilize these data in conjunction with high-level policies that consider locale specific data to produce suitable formulas and schedules. In other words, precision feed has two dimensions: there is the data dimension identified above, and there is the action dimension. The extent to which schedules and formulas can be independently applied, both to an apiary site and the individual colonies, determines the degree to which precision feed has been achieved.

Perfect precision in feed methods requires that any number of individual data from any number of individual colonies at any apiary site produce a specific formulation of any number of ingredients deployed to specific hives on highly individualized schedules. This emerges as our rubric for evaluation. Given the challenges involved with data collection, management, analysis, formulation and distribution of feed in large apiaries, this is no small goal to set for the future of apiculture. It is therefore necessary to begin with a look at the problems beekeepers try to solve.

II. Challenges in Apiary Management

It is important to evaluate the challenges facing apiculture today to understand the way precision feed practices could meaningfully benefit apiculture. Any existing cultivation practice is going to be built around real problems that vex beekeepers. Starting with an apicultural perspective provides a solid framework for analysis. Various individual solutions differ greatly. However, an important place to begin constructing this perspective is with a look at these problems, rather than particular solutions. Some of these existential issues at the heart of most apicultural activity are examined here.

Colony Collapse

No beekeeper likes to see his bees die and lose hives. This is both costly and a stewardship failure. Of course, some hive loss is expected and can be reasonably managed. But when the losses are large, there are significant economic costs that come with the unplanned reduction in apiary size. There is an immediate loss of productivity. Lost colonies must be restored. The cost of cleaning out and replacing hives is significant and the productivity of new colonies is generally lower than larger established colonies. It takes time.

Even with new developments in understanding honeybee health and disease coupled with advancements in medications and treatments for common causes of honeybee death, hive losses continue to be stubbornly high. During the summer of 2020, the winter of 2020, and the summer of 2021, total hive loss for the U.S. was recorded at 45.5% [3]. This was the second highest loss on record, 1.8% higher than the previous season and 6.1% higher than the ten-year average [3]. Colony loss continues to be a major concern for the industry.

Disease

Colonies that do not collapse, may still suffer from disease. There are many ailments that effect bees. Many of the same diseases affect colonies across the country and often there is predictability year over year in the types of disease and severity found in an apiary. For example, a U.S. government survey that covered the period between 2020 and 2021, identifies varroa mites as the number one stressor of hives in the United States [4]. With predictability, preparedness should be possible. Yet, this is not always the case. Predictable ailments do not always occur with predictable frequency or at predictable times. And sometimes new types of disease are encountered. In the same survey, 8% of hive loss resulted from other pests or parasites, and 5.4% of loss was from completely unknown causes [4]. When a disease hits an apiary, it often does not affect all hives equally or at the same time. Treating all hives equally may exacerbate a problem or even cause new ones. The ability to diagnose and respond accurately and rapidly is important for preparedness in order to minimize the impact.

Climate Change

The unpredictability of weather can also play an important role in apiary management and honeybee health. Sometimes climate variation is benign. Other times, it can be significant. For example, the last decade in California has presented some unusual challenges as the weather diverged from more typical seasonal patterns. Frequent drought creates unpredictable forage. Excessive drought can significantly impact honey flow. Even between two drought years, the impact can vary. In 2017 in one locale in central California, there was higher spring rainfall, while fall and early winter rainfall was virtually non-existent. In the years prior, the reverse was true. These dramatic fluctuations create corresponding flow and dearth. Added to this, frequent wildfires now create even more unpredictability. Excessive smoke can linger for months and does seem to affect honey reserves and thus feed requirements. From personal experience in 2008 and 2016, this appeared to amplify a seasonal dearth that usually occurred at the same time in late summer. Because of this and other factors, colony population growth can be affected and become unpredictable. This affects swarming behaviors, which are an important focus of apiculture affected by weather [5]. “Reproductive swarming depends on favorable environmental conditions” [5]. Again, from personal experience keeping bees in California, swarming behavior can begin as early as February and sometimes not until late May. Feed is often used as mitigation. Koeniger and Koeniger describe this relationship as “specifically, ample pollen and nectar must be available for two reasons: to produce enough bees before colony fission and to support the swarms which do not have combs or any honey storage at the beginning” [5]. Climate unpredictability can dramatically affect forage, and thus affect swarming and mitigation strategies including the type, timing, and quantity of feed required.

Site and Microclimate Variance

General climate patterns are not the only consideration. If climate in general is of importance in apiculture, then any significant variance in local conditions would also be equally important. Each site can have its own unique microclimate that affects hive strength. “The dimensions of any particular microclimate are highly dependent on the mobility and dispersal capabilities of the organism in question” [6]. Bees have an effective forage range of about two miles. This is sufficiently narrow to be affected by many microclimate conditions. August in California is usually extremely dry. And this leans hard on the bees. Yet temperatures may differ dramatically near the coast versus inland. Mountains can affect cloud cover and rainfall. Even within a radius of a few miles, apiary sites can be quite different. In the last ten years, microclimate effects have been made even more pronounced by the unpredictable local drought and wildfire conditions described above. Microclimate management is an important factor in precision agriculture for wireless sensor networks which can be applied in apiculture [7]. In addition, some locations have other environmental considerations such as noxious blooms that are sometimes addressed with a feed strategy [7]. For example, "California buckeye (*Aesculus californica* (Spach) Nutt.), common mainly in California, is the best known and documented of such plants" [8]. It is found in some locales and the nectar is toxic to bees. The importance of toxic bloom "depends somewhat on weather, which may favor the bloom of the toxic species more than the others" [8].

Operational Costs

Apiculture enterprises are cost sensitive. Large apiaries must consider the economic impact of any management strategy. Labor, measured in man-hours, is found to be among the factors "adjudged significant variables affecting the production of honey" [9]. There is a demonstrated positive correlation in labor to productivity. Yet, labor costs can also be significant. Honeybee farming cost analysis determines that labor costs represent 81.3% of all recurring costs [10]. Therefore, while hive health is important, the benefits of maintaining strong hives with high productivity must be balanced with the costs of implementing any changes that might achieve better results. A careful cost-benefit analysis is part of any evaluation of cultivation method and labor is a big part. Of course, the cost of labor can also vary by locale as well. For example, labor laws and other factors unique to some states can result in labor cost variance without necessarily a productivity correlation. Therefore, the viability of an intensive management strategy that is heavily dependent on labor might be different for different regions. Given that there can also be additional environmental challenges in some states as shown above, the survival of some enterprises may rest on their ability to implement effective cultivation while managing these costs within sustainable parameters.

Market and Competition

The other side of the equation is income. While there is some leeway, not all costs can be passed on through higher prices due to market and competitive pressures. There is a limit. For any apiculture endeavor, the per-hive maximum income can be reasonably estimated to identify that upper limit for management costs necessary to maintain a sustainable enterprise. For example, in 2011, hive rental costs for the most lucrative crop, almonds, was between $121 and $172 per hive [11]. The average was around $139 per hive [11]. Many of the beekeepers surveyed participated in multiple crops in a single year, which means they were able to rent some of their hives more than once a year; the average was approximately 4 times. Averaging the total revenue from the top four crops in the report ($22,190,508) with the largest total number of hives required to service any single crop (118,850) yields an average total revenue of about $186 per hive per year. The study analyzes the revenue of a subset of the survey respondents and finds that these beekeepers generated 69% of their revenues from pollination services, 28% from honey, and 4% from other sources [11]. Pollination fees do change from year to year. For example, rental fees were up for almond pollination in 2014 at between $170-$200 per hive [12]. Forecasts for 2015 predicted prices to be about the same [12]. However, within any year, the beekeeper is still constrained by the prevailing market rates.

While the majority of revenue comes from pollination services, honey is a substantial component. In the example above, it was 28% [11]. Unlike pollination services, honey can be subject to global competition. An effective marketing strategy can work to achieve a premium for local honey over global market prices. For example, in trendy locations like California, there is a public awareness that honey can have different qualities, and people are willing to pay a premium for these differences. However, this strategy diminishes as the beekeeper pursues a larger distribution by scaling the operation and expanding the market. Ultimately, this should approach the global price.

For both pollination services and honey, different marketing strategies can produce different results. Yet, even accounting for such variance, economic realities impose limitations on methods a beekeeper can realistically deploy. The revenue estimates above set a maximum operation budget to maintain sustainability. With disease, hive losses, weather, labor expenses, and pricing pressures, there are a lot of things over which beekeepers have no control. It turns out that many of the challenges of apiary management are affected by the wide variation of performance from year to year, from site to site and from hive to hive. Beekeepers that effectively manage this variance to produce a quality, consistent product no doubt improves the competitiveness of their brand, and would enable more operational cost to achieve these results. While there is this pressure to improve cultivation, these real limits must be recognized.

III. Feed Practice as an Essential Cultivation Tool

Considering the six apiculture challenges above, a feed regimen is relevant to all six, and something the beekeeper can actually control. While beekeepers develop unique adaptations of feed strategies for their apiaries according to personal cultivation philosophies, it is an essential tool broadly applied to address common apiculture objectives.

Common Use of Feed

The United States Department of Agriculture identifies the benefits of honeybee feed practice and outlines ten common reasons that feed is used in beekeeping [13]. Among these, management of pollen and nectar shortages during times of dearth and suboptimal locations are mentioned.

Incompatibilities between weather, natural forage availability, and brood and honey flow schedules are key reasons for feed use in apiculture. Feed can also be used to nurse colonies which suffer unexpected adverse effects, such as pesticide exposure [13]. When using feed practices to achieve these goals, there are considerable variables that must be managed in an effective strategy. The key to feed strategy is to manage situations where the needs of the colony become out of sync with the natural conditions and "natural food sources (pollen, nectar, or honey) are inadequate or not available" [13]. This highlights relevance of apiary management and feed. There are many factors which the beekeeper cannot directly control and which ultimately determine if stored food reserves are adequate to maintain colony strength. Geographic seasonal differences can significantly affect colony needs in different locales [13]. For example, brood rearing continues throughout the winter in some areas such as the South and Southwest United States [13]. This is not so for colder northern climates. Therefore, these differences translate into higher winter food requirements for the southern colonies, and may therefore benefit from feed strategies not necessary elsewhere [13]. This is consistent with the challenges imposed by climate change and site or microclimate variance. For larger operations, there is no one-size-fits-all strategy. Methods must accommodate these differences.

Microclimate Response

Since different regions impose different nutritional requirements for wintering, if feed is being used to supplement forage it is natural to infer that those different regions could also impose different feed requirements. For example, in Central California there can be localized granularity in requirements due to site variance. A common approach is to modify feed strategy to account for this variance to ensure maximum colony development. Colony development is identified as the first common use of feed in the ten practices noted above [13]. In each Central California microclimate, honey flows during any particular seasonal period may be simply inadequate to sustain robust colonies. Without supplemental feed, hives dwindle. Much discussion and literature stress winter as the most sensitive season. However, personal experience in temperate climates such as dry arid regions of Central California show that summer can be much harder on bees than winter. There is almost no rainfall from May until September making nectar very scarce by August. After several seasons of significant losses in August, even following strong spring and early summer build-ups, it became important to watch this time much more closely. When forage disappears suddenly, it places severe stress on the bees. As experience develops with behavior signals, behavior change could be attributed to these factors. The bees become edgy. They have a more desperate feel. They often start fighting with each other. From a human-oriented interpretation, they appeared annoyed as they search flowers in vain. Anthropomorphic analysis aside, this stress does seem to take its toll. Apiaries only ten miles apart may show very different signals. Yet, when a well-managed feed program is implemented, palpable calmness returns and colony vigor is maintained. With the larger colony size, the bees are more productive when the natural honey flow returns. Indeed, the USDA findings [4] bear out this experience with data showing that while winter loss is larger, total hive losses from April through September period is also significant at 39%. This is further evidence which suggests feed strategy could be applied to address expanded geographical conditions.

Population Stability

Empirically beekeepers learn that nursing the bees through these tough periods including summertime helps maintain colony sizes and significantly reduces hive loss; these strategies are found to be particularly beneficial for managing hive population size [13]. Adding further justification, there is evidence that nutrition does affect the survivability of honeybees under stress. A study done at Oregon State University demonstrated that honeybees had greater survival rates when fed a solution of pollen, cellulose and sucrose syrup [14]. The formula seems to matter. This makes sophisticated science-based precision feed quite challenging in practice and points to an opportunity to further develop the theoretical relationships between stressors and nutrition and integrate this knowledge into precision feed strategies.

Administration of Medicine

Much of the research so far looks at nutritional motivations for supplemental feeding of honeybees. There is now a new reason to implement feed in apiculture: the administration of medicines. The use of feed-based medicines has increased significantly since the 1970s. For example, Nosema is a big challenge most beekeepers must manage. And of course, one of the primary medications for Nosema, fumagillin, is administered through feed. Realities concerning the use of such treatments require careful planning around honey flows and colony feeding vigor. The time for action on Nosema is usually fall and/or spring, just after or just before the honey flows. It is at these times where product contamination can be mitigated and hives take medicated feed in sufficient quantities to be effective. Winter treatments are more problematic. While Nosema does strike in the winter and can be devastating, treatment with fumagillin is more difficult due to the fact that efficacy of administering feed-based medication is dependent on feed take, which is impaired by typical winter conditions. When it is cold, the hives will not take the medication fast enough. The beekeeper is placed in the unenviable position of helplessly watching his colonies suffer. Yet, not all winter days are equal. If the beekeeper is patient, there are often short warm periods which create windows where activity increases and medication can be given if he is ready. The timing of these windows is highly dependent on unpredictable seasonal and microclimate variation. One side of a ridge might be completely different than the other. When a window appears, the beekeeper must be ready and act, or the opportunity passes; and sometimes the hives pass too.

As discussed, Nosema treatment is accomplished primarily through feed. A common treatment contains the antibiotic fumagillin. Another challenge for using this treatment is that the efficacy of fumagillin products in feed has a short life. Effectiveness can diminish after just a couple of days. Ideally, treatment is mixed and dispensed in the same day. As it sits mixed in jugs or feeders, it loses potency, requiring retreatment. For large apiaries, waste is a significant cost concern. Therefore, it is important to make and administer each dose as efficiently as possible.

Adding even more complexity to the task, the rate of take is dependent on colony population size and vigor. The bees must take the medication quickly. The potency of Fumagillin-B, a fumagillin product is preserved longer in honey [28]. Therefore, if the disease is accompanied by a diminishment of vigor, which is often, it can make treatment less effective when it remains in the syrup. For maximum efficacy, diagnosis and treatment must be swift and come before this effect. Even short delays can be significant. Yet, as seen, effective treatment must also occur in the appropriate seasonal periods or in incompatible seasons, during narrow opportunistic weather windows. This suggests a complex, multi-dimensional planning problem. Thus, managing the timeliness of administering these medicines can be quite challenging. A reasonable amount of data and action must be coordinated efficiently for success of these feed-based treatments.

While Nosema is one of the more common applications of feed-based medication, there are other diseases treated through feed as well. For example, foulbrood also has such a treatment option. Treatments for foulbrood include: oxytetracycline, tyrosine tartrate, and lincomycin hydrochloride. Using these antibiotic treatments effectively, as with the fumagillin example above, can save colonies from costly alternatives, which for foul brood is the complete loss including the destruction of the bees and all hives and equipment by incineration. Effective treatment is economically advantageous keeping the bees alive, maintaining productivity, and eliminating the loss of hive equipment and restoration.

The challenges of efficacious use of feed-based treatments are likely to increase as the use and complexities of new products continue to grow. For example, Varroa mites have been identified as the most common hive stressor [4]. At present, it is not common to treat Varroa through feed. But this is changing due to technological advances. There are now experimental RNA interference treatments for Varroa administered through feed. These treatments are showing promise in the control of this prevalent and destructive pest. For example, a large-scale field application test of RNAi technology showed success in administering RNAi technology to approximately 160 hives in two locations through feedings to colonies in ½ liter doses approximately twice a week [15]. While these RNA treatments are still new, they show similar, if not more stringent, potency constraints as found with the more traditional feed-based antibiotic treatments above. There is evidence that loss of potency in syrup feed will continue to be an issue even with new technology. Loss of potency in dsRNA mixed with liquid feed can be traced to bacterial and fungal contamination [16]. This stresses the importance of precision of application immediately after preparation in context of the environmental cycles that are noted with feed-based requirements above. At least two companies, Beeologics, acquired by Monsanto, and Vita, a company based outside of London, were actively pursuing this technology as treatment for Varroa in 2013 [17]. Several years later, Bayer acquired Monsanto. The COVID-19 pandemic has brought more even greater awareness of the benefits of RNA technology to the general public, along with unforgiving distribution requirements, such as freezing. In 2021, GreenLight announced it had acquired RNA technology from Bayer and is actively pursuing products for feed-based RNA Varroa treatments [18]. Therefore, development of this approach actively continues, and it can be expected RNAi will play an increasingly critical role in future hive treatments.

IV. Alternatives to Feed-Based Treatments

If feed-based treatment can be complicated, it is helpful to consider simpler alternatives. Yet, many of these can be equally challenging, if not more so. For example, from personal experience as a beekeeper, there is little awareness of any proven effective alternative treatment to Fumagillin. There were, however, other cultivation strategies which can be used. These are mainly focused on general health, such as ensuring suitable hive locations, maintaining equipment to keep bees warm and dry, seasonal sterilization of hive wood through brazing, and isolation for infected colonies. Each of these had their own related costs and challenges. Yet, there always seemed to be a need to return to feed-based treatments because bees would still get sick. Feed-based Varroa treatments were not readily available at that time. Therefore, other methods were used. As a preventative practice, screen bottom boards can keep mite populations down. For infestations, amitraz strips during off-season infestations were effective, and powdered sugar dusting for severe summer infestation is another technique. Both of these are very labor intensive and required a complete break-down of hives, either to install the strips or to dust the bees. Handling amitraz required additional precautions including permits, storage, special gloves, and the safe disposal of used strips. The timing of these operations was often inconvenient as well. For example, winter hive breakdowns exposed bees and brood to cold temperatures. Summer hives were large and heavy. And powdered sugar treatments were harsh on the bees. Some beekeepers used formic acid as an alternative. Hive break-downs are not necessary for the application of formic acid, but it can be an unpleasant substance to handle and also requires additional storage, handing, and disposal precautions. This highlights an interesting issue. Every unique treatment method requires unique field skills. This increases the training burden. Ideally, an investment in one skillset can be applied to as many field situations as possible. A versatile method such as precision feed has this potential and is therefore very attractive. Skills developed in the mixing, handling, and dispensing of feed can be applied to any formula targeting any disease. Further, feed equipment can also be generally used with any formula and any schedule. The main challenge is the analysis of data and adaptation of formulas and schedules to the actionable diagnoses.

The Role of Data

Intelligent action requires relevant data. Precision action requires precision data. Data are integral to any precision-feed approach. Cerosaletti and Dewing, referring to Precision Feed Management (PFM) in dairy, stress the importance of data [1]. They assert that “because PFM is measurable, it’s manageable” [1]. In apiculture, the critical cycle of diagnosis and action has been demonstrated. This cycle expands to include data acquisition, diagnosis, and action. “Precision Apiculture system [sic] can be implemented into the practice similar to Precision Agriculture approach completing three stages: data collection, data analysis and application of control action” [7]. This cycle is repeated to monitor the efficacy of action and take further steps towards an optimal solution.

Broad data are available in apiculture. Yet, effective methods require the selection of the best data, and the necessary analysis, for determining the best action. And cost-effective methods require the selection of data readily collected. Data that do not drive action is operationally irrelevant. Data that cannot be collected when needed are equally unhelpful. In fact, the more precision in relevant data, the greater opportunity for precision in action. Any practical solution must depend on practical data that can be collected at the proper time and frequency.

There are several experiences in apicultural operations that are good examples to guide discussion on this point. It is insightful to consider the two apiculture diseases discussed above : Varroa and Nosema. Both are serious problems that can result in substantial colony loss. Both maladies can affect a hive exponentially, starting off slow and at some point, quickly moving past the point of no return. With Varroa, actionable diagnosis requires observation and measurement. And the most precise way to monitor an infestation is to count mites. One recommended method is to count mites that drop to sticky paper placed at the bottom of a hive in a specified time. In the field, this proves challenging. Provisioning and handling of the paper is a burden. Debris quickly reduces the effectiveness as does feed spills, rain, and many other conditions. Even when exact, objective counts were possible, accuracy is an issue due to the discrepancies caused by these factors. Field improvised short cut can be used, for example pulling just a few frames and counting the mites which can be seen on live bees. Mites observed on larvae usually indicated the infestation had reached an advanced stage and it was time for action. Therefore, this observation is significant. Typically, when these observations are first made, population vigor is still strong. By the time the condition has progressed and populations show signs of weakness, it is often too late. Treatment is less effective. All this monitoring is labor intensive and invasive. Therefore, at times, if one colony was observed to be suffering, treatment is applied prophylactically to the other hives in the same locale. Full apiary inspections are important but time consuming. For Varroa control, the difficulty obtaining precision data made precision action difficult.

The principles of Nosema diagnosis were similar. Precise diagnosis required spore counts. Spore counts required collecting samples of bees from each hive. These needed to be processed and then observed under the microscope. Spores are then counted to estimate the level of infection. This is a lot of work, especially for large numbers of hives. However, problems could often be deduced through simple observation of abnormal entrance behavior, which was much easier. Of course, for certainty, spore counts are necessary. This level of precise diagnosis is generally prohibitive, and therefore cultivation often relies on field observation and seasonally-based treatments. Spot-checking spore counts is another field short cut for increasing precision to monitor and tune seasonal decisions when true data-driven precision treatment is too expensive. These experiences show how the pursuit of precision in apiculture is always in context of these types of cost-benefit analysis. It is difficult to collect more data when there is work to be done.

Fig. 1 Hive weight recording using automatic hive monitoring system: Weight data collected automatically from an active hive and transmitted to a website for review; Weight data can be collected in real-time for any number of hives and is easily interpreted for indications of activity and potential problems

In 2016 through 2017, we evaluated automated hive monitoring equipment through a partnership with the Bayer U.S. Bee Care Center in North Carolina. This included remote hive monitoring hardware developed by the company Agrisound, also known as Arnia. This technology collected a range of data from the hive and automatically uploaded it on a regular schedule to a web-based monitoring system which could be reviewed and forwarded to the scientists at Bayer. The system collected basic information like interior and exterior temperature data and hive weight, as well as more exotic data such as hive sounds. The results of this trial experience provided some key insights into the automation of data collection. For example, it showed that hive weight is an extremely important and actionable decision tool. In the period from February 13th to February 15th, general weight drop is observed. From February 15th to February 18th, a general increase is found. Weight gain during honey flow can be seen literally, and weight loss during dry periods immediately shows when supplemental feeding is necessary. Weight derivatives show both population size as well as feed take rates. Mid-day weight drop of approximately 1.5 kg shows the size of the forage population. Each bee weighs approximately 0.0001134 kg. A quick calculation finds an active forage population of around 13,227 bees on February 13th. Similar analysis shows that on February 17th, about 4,409 bees returned home early before noon and they seemed to stay home on the 18th as well. Weight data were readily available and actionable. Temperature data were also easily collected. In healthy hives, brood temperature remained constant at approximately 32 °C. However, when hives became week, the internal brood curve would begin to resemble the external temperature signal. Sound data, one of the features of this system, were not as easily applied to cultivation in the evaluation. This showed that some data would require more research and post-acquisition analysis to ultimately benefit in practice. The trial lasted only two seasons, yet it was a powerful demonstration that data in general, and automated key data in particular are significant and essential for intensive precision feed strategies and could benefit from further research.

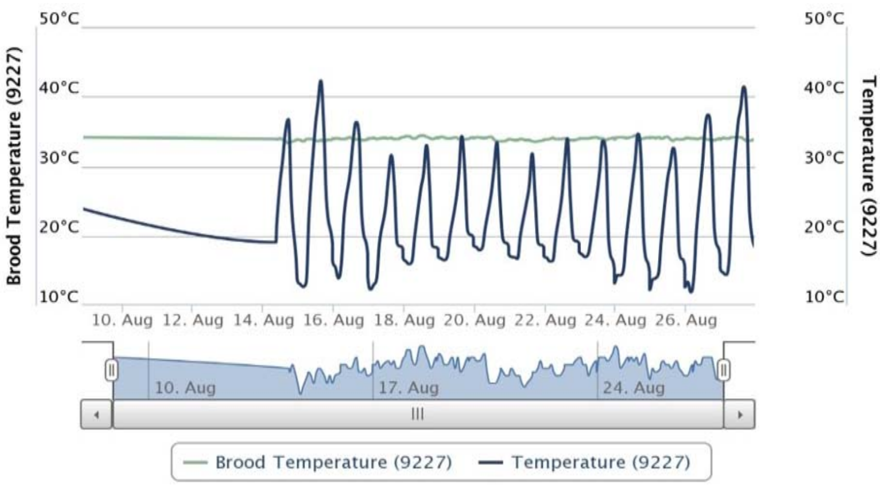

Fig. 2 Hive temperature recording using automated hive monitoring system: Temperature derivatives and interior/exterior difference also proved readily available and operationally useful; exterior temperature fluctuations can be compared against the constant brood temperature in a healthy hive

V. Objections to Feed in Apiculture

Use of feed in apiculture is broadly accepted, but not unanimous. Some beekeepers have strong beliefs against using feed. Commonly cited reasons are: nutrition, quality of feed ingredients, efficacy, economic exploitation, attracting pests (ants, wasps, etc.), hive pH, and swarm management. While the nutritional requirements of the honeybee are not unusual [13], it does not necessarily follow that feeding them is straight forward or proven effective. Exploring these objections serves to illuminate additional difficulties using feed strategies in the apiary.

Bees do not live on sugar alone. In addition to carbohydrates, honeybees do require proteins, lipids, vitamins, minerals, and water [19]. Therefore, a sophisticated precision feed practice would consider overall nutritional impact. This is sometimes cited in objections to feed, with emphasis placed on natural forage. Most feed practice does depend heavily on carbohydrate sugars, and some provide protein supplement as well. A pure sugar syrup does not have all of the nutritional components that honey bees require. Therefore, a diet exclusively carbohydrate is likely to have health consequences. Beekeepers sometimes adjust nutrition usually according to different theories on seasonal requirements. However real-time decision data are lacking to make precision adjustments on a colony-by-colony basis.

There is also active discussion about different sugars, and whether some may be more beneficial, and even whether some may be detrimental. Feeding high-fructose corn syrup, a common practice, seems to elicit the most negative response. Much of the objection is based on circumstantial principle. This type of sugar is not a naturally occurring sugar to which bees would be exposed through nectar. And there may be some scientific basis to be cautious with the use of high-fructose corn syrup. Fructose contains a compound called hydroxymethylfurfural (HMF) which increases over time [20]. Apparently heat increases the accumulation and this can be toxic to bees if it reaches high enough quantities. There is also research on HMF that shows greater efficacy of honey and sucrose syrups over high-fructose corn syrup [21]. The likely reason for the widespread use of high-fructose syrup is ease of use and cost.

Some question whether feeding makes any difference at all. A survey conducted in 2011-2012 finds no correlation between any feed practice and higher survival rates [22]. The statistics also show that feeding bees honey might actually result in higher hive losses [22]. Without further analysis of the data, this would seem counter intuitive, and there is reason to hesitate before broadly applying these findings. Specifically, the 2011-2012 survey was high-level and uncontrolled, and there may be many factors that produced these results. Common experience with beekeeping finds challenges correlating annual performance to any particular cultivation practice. There have been many cases when bees are nursed through difficult times, only for the hives to be knocked out later in the season by another problem. Yet, it is common for beekeepers to avoid feeding their bees outsourced honey, mainly due to the risk of spreading disease. An improperly controlled experiment could show similar results if unsanitary conditions were to increase disease, even if nutritional requirements had been ideal. Never-the-less, feed likely will not always save the day. Apiculture is a complex system, and it is difficult to discern these relationships without carefully constructed research.

Another moral-based objection to feed is economic exploitation. While this is sometimes expressed as a categorical rejection, the primary concern seems to be diminishment of the well-being of the honey bee primarily for economic benefit. Often there is an implicit belief that the gain of the beekeeper must necessarily be a net loss for the honeybee creature. The usual example given is that beekeepers use a feed strategy to overharvest. The overharvesting of honey coupled with complete replacement with nutritionally inadequate sugar syrup is an inequitable swap. While this practice is not common, it is not unheard of in beekeeping communities. Anecdotal stories circulate of unscrupulous beekeepers that simply let bees starve after overharvest, finding it more economical to simply restart colonies that did not make it in spring. While this may occur, it does not necessarily invalidate all feed practice. It is important for commercial enterprises to resist exploitive practices, but reducing all feed practice to exploitation is oversimplification. There is even some evidence that no-harvest strategies can precipitate honey-bound hives, which squeeze brood size and eventually lead to swarming and complete abandonment. In fact, apiculture might be one of the agricultural systems where true mutual benefit is possible, and even those that decry feed practice usually caveat: except in emergencies.

Another problem is that feed can attract pests. These include ants, wasps, and honeybee robbers. Certain feed systems are better for deterring pests than others. For example, any feeding system that maintains food outside the hive, or close to the entrance, becomes a temptation of varying severity ranging from nuisance to hive threat. Technology that places the food completely inside the protection of the hive, combined with appropriate seasonal use of entrance reducers to make the hive more defensible can alleviate some of the stress from predation that feeding can cause. But even interior hive feeding can be problematic. Ants easily exploit weaknesses in hive integrity, and liquid syrup during some seasons can cause mold and excessive humidity. Selection of feed technologies should consider these issues.

Honey and sugar syrup have different pH levels, and some beekeepers are concerned this is important to colony health. On average, honey has a pH of about 3.9. A sucrose syrup generally has a pH of around 8. Inverted sugar syrup, usually made by adding ascorbic acid to sucrose sugar, has a lower pH level, and different sugar compounds which closely resemble sugars in honey. The sucrose is broken down into glucose and fructose, common sugars in honey. For this reason, there has been research using inverted sugar syrups in apiculture. These have had mixed results. Early attempts to use inverted syrup resulted in poisoning. This was found to be due to concentrations of HMF in the invert sugars [23]. Inverted sugars without HMF had similar results to non-inverted sugars. Most beekeeper discussion on pH seems to focus strictly on pH difference between sucrose and honey, reckoning that something different must be less natural. However, skeptics must keep in mind that bees forage not on honey but nectar. Nectar has been found to be in the 4.2 to 8.5 pH range [24]. Therefore, an assessment based solely on comparison with honey is likely inappropriate.

Anecdotal claims are also made that overfeeding of bees can result in health issues and lower vitality. The general principle here is strength through striving; lazy bees must somehow be less healthy. There is little research evidence to support this belief. It is mentioned here mainly for completeness.

VI. Challenges of Feed Practice in Apiculture

Basic feed practice in apiculture is the consistent collection and interpretation of data coupled with effective, timely action. The common uses of feed in apiculture have already been explored, as has feed as a method of medication, and the importance of precise data for driving precision action. The apiculture system is complex. This complexity projects onto precision cultivation presenting a formidable challenge. Feed requirements must be continually estimated from data which model many different influences. These requirements must be translated into effective actions, which include formulas and schedules and consider implementation costs. Further, additional constraints such as spoilage and loss of efficacy must be included. Feeds have variable shelf and field life. And medicated feeds often lose potency quickly. Therefore, to be effective, a feed response must be reasonably timed with requirements within these parameters. All this must fit within the available means of the cultivation context. These challenges are examined more closely below.

Predicting Variance

As seen in the challenges for apiculture in general, unpredictability of weather compounded by microclimate can play an important role in apiary management and honeybee health. This challenge presents an opportunity for precision feed; an opportunity to manage these cycles. Yet it is also a challenge for the practice itself. Feed strategy is often simplified at a macro level into seasonal schedules. Due to the difficulty in mobilizing resources, adapting schedules to unpredictable high-frequency climate variation can be impractical. Retrospectively, this frequently results in sub-optimal feeding schedules. For example, weather might turn out cooler than desired, or the hive build-up cycle might have occurred earlier than expected. Therefore, availability of data which serve as leading indicators of key feed events is of critical importance for precision feed strategy. Further, these data must be coupled operationally with flexible formulation and scheduling capability, easily adapted to variance.

This complexity is complicated by the fact that individual colonies respond differently and take feed at different rates. This too can be unpredictable. Even a colony that is strong one year, might be slow to build the next season. And feed requirements also vary from colony to colony. An experienced beekeeper often responds with adaptations in the field. However, this method is challenged by practical considerations, especially when scaling using less skilled or inconsistent labor. New labor often is unable to make the necessary field observations, requiring a skilled beekeeper in the field during procedures. And if the same individuals do not tend the same hives, patterns are hidden without careful records and analysis. An alternative is to generalize actions and apply a one-size-fits-all strategy with the obvious waste that results. Personal experience confirms that beekeepers are constantly faced with these challenges and must experiment with many different management approaches. For example, when it comes to data collection and assessing variance, the frequency of inspection is important. Nyquist's law of sampling determines the frequency of inspections at roughly twice the cycle rate. Therefore, the labor cost for precision can double as well. During inspections, voracious hives are replenished while meek hives are allowed to keep eating, or the tray can be emptied and either refreshed with a reduced quantity or allowed to stay empty for a cycle. A field marking system or logs to identify which hives require attention and which do not can be useful. With a separation between data collection and cultivation action, less experienced beekeepers can perform the routine servicing.

On a personal level, many beekeepers enjoy spending time in the apiary watching and tending the bees, even if only making small adjustments. However, as a business operator, the costs make this difficult and limit the number of managed hives. Manual, experienced data collection was expensive and error prone. Field shortcuts would often preempt strict methodical practice.

Managing Labor Schedules

The lack of predictability often clashes with operational management in the development of efficient labor schedules. Apicultural activity is not year-round. It is common to use temporary labor. But this requires planning. The ideal is to plan the cultivation schedule, including feeding, in advance. Then material and labor can be efficiently managed. Material acquisition can be optimized. Temporary labor availability can be secured. When requirements are unpredictable, management is a lot more challenging. Weather variance discussed above is a big factor. If there is advance notice of warmer days ahead, feed schedules and labor can be adjusted for efficiency. If there is inflexibility in the labor schedule, these adjustments cannot be made without hardship. Likewise, disease can come at different times. When using feed-based treatments, this has a similar impact on the labor schedules.

Managing Spoilage and Potency Loss

If conditions are not suitable, colonies will not take feed. When conditions are inadequate, it is inefficient to deploy feed early, as it can spoil. Further, the use of preservatives may increase the window, but it still will not last forever. Also, as discussed, feed is best administered immediately after preparation and ideally all feed is taken within a couple of days of mixing. Unconsumed feed typically becomes contaminated in a short time, often within a week, as many feeding tanks are open, to allow bees access and contaminants are introduced as bees make contact, which accelerates spoilage. Once spoiled, bees usually do not take food and it must be dumped.

When using feed to dispense medicine, timing is even more crucial, as the medicine must be also consumed quickly before it breaks down. Further, the cost of medicated feed is much higher than syrup alone and waste is more expensive. Therefore, intensive feed capability must include the ability to mix and deploy formulas immediately before consumption.

When hives do not take feed, or the equipment can also become contaminated; the reservoirs need to be cleaned out. This creates additional material and labor burdens. Unused feed and medication must be removed. After heavy contamination, feeders must be rinsed and sometimes sterilized. After this, feeding can resume at adjusted rates. The added step of dumping spoiled feed before replenishing might not seem important, however it can be, especially with large numbers of hives. Feeders usually must be removed completely to empty and clean. Given that it does not take long to feed a single hive, the extra step is significant when working large numbers. Intensive feeding without diligent monitoring and adjustment can be wasteful and expensive.

Inadequate conditions, contamination, spoilage, equipment maintenance; these challenges add up to increased recurring material and labor costs when using feed in apiculture.

Collecting Precision Data

In a typical apiary, data acquisition is integral with feeding activities. Personal experience managing hives over ten years provides insight into data collection practices in beekeeping. Feed take was recorded in logs as it was dispensed, and adjustments were made accordingly. Data on feed-take rates were not only important for these corrections, but a significant measure of hive health. When bees vigorously feed, it is an indication they are strong. When this activity is slow relative to the season, even when colony size is still large, it can be a leading indicator of future problems. This value was integrated into the practice, and logs were regularly reviewed to make judgements about apiary health. Therefore, recording these data is an important part of overall apiary management but keeping precise data records can be time consuming and invasive.

This data recording was not particularly precise. Nor was it automated nor computerized. The technology was paper and pen. This created particular difficulty in the field. Some of this difficulty is just part of the apiary environment. Hands are often covered in propolis and honey. This soils the records. Honey and syrup often contaminate the records as well. And the pen does not write well on wet or heavily soiled paper, so records must be scribbled around these spots. Eventually, a coded system was developed with a standard chart that facilitated record keeping and apiary workers were taught to use it. This narrowed but did not eliminate subjective interpretation and inconsistencies of data between workers. Hives also had to be tracked as they moved around. Individual hives were referenced by unique colony serial numbers. But apiary charts had to be manually updated when hives were moved. Meaningful interpretation needed to correlate with the new microclimate data. Therefore, when hives moved, the data had to be normalized to the new location. The imprecision of human-biased pen-and-paper techniques slanted analysis towards art versus science.

Data are more useful when they can be correlated and analyzed across multiple seasons. Paper records soon outlive their usefulness. By default, correlations and conclusions are recorded, and these higher-level summaries are compared across different seasons. This was more efficient from a data processing perspective, however, it interfered with retrospective analysis. For example, our area experienced significant colony loss one winter. It was observed in our apiaries that this loss occurred during a specific week during an unusual weather event. Discussions with other beekeepers later that spring revealed similar loss rates, but these beekeepers had not kept detailed data. It was impossible to go back and reassess the diagnoses to account for these new observations. Keeping multi-year records require the entry of detailed manual apiary data taken throughout the year into a system where it can later be worked. This extra step added more costly office work. Often, for this reason, it is not done. Therefore, the automation of data collection and analysis is extremely relevant. As seen above, hive weight data from remote sensors showed tremendous potential to provide objective and readily available data for population size, replacing the subjective and labor-intensive method of visual observation and manual paper-pen recording. Data can be collected as frequently as necessary without any additional cost. Further, additional analysis of such raw data can eliminate the need for other types of manual records. For example, manual feed logs were discussed above. Automated weight data would make these logs redundant. When hives are fed, there is a sudden increase in weight. This corresponds to the added feed. A low pass filter can determine overall hive growth, while higher frequency analysis can show added feed in addition the forage population size calculations done with intraday fluctuation. Different information can be deduced from one dataset. In ways such as this, the ability to objectively measure relevant hive data and perform additional analysis has potential to enable more sophisticated feed and apiculture strategies.

VII. Conclusions

Feeding helps build large healthy hives [13]. In many situations, it is one of the few things a beekeeper can control. It serves a role in the management of diseases. It can provide relief from stresses of unpredictable climate variation. And it can mitigate the impact of natural disasters like wildfire or drought. These are critical apiculture objectives. Large healthy hives mean higher productivity per hive which relieves cost and competitive pressures. These results find that the benefits of feed strategies are numerous. While managing these challenges may create additional costs, intensive precision feed methods can significantly extend these benefits in apiculture. These benefits have the potential to reduce colony loss and improve the pollination and honey productivity of the apiary.

This research finds a significant opportunity for precision feed in the efficacious administration of medicines for disease management. This includes medicines already in common field use along with promising new experimental technologies such as RNA treatments. Through precision feed, apiculture can efficiently realize and advance the promise of these remedies within complex parameters and ultimately keep more colonies healthy and productive. Many practical challenges create trade-offs between management of the bees, cultivation practice, and the optimal use of these tools. For example, prophylactic use of some medicines might optimize work schedules, yet be unnecessary and wasteful. Targeted administration might undertreat or come too late due to management challenges. As medication becomes more sophisticated, so will these challenges, including managing dosing in a highly fluid environment. The difficulties of tracking treatments and administering proper doses over a large number of hives at precise times will tax current cultivation practices. Apiculturists need more sophisticated tools to help them overcome these complexities. For these technologies to be successful, cultivation practices must also evolve.

While advancements in medication treatments target specific diseases, sometimes the best cure is prevention. Managing strong, health hives may be the most important focus a beekeeper can have. The ability to easily implement feeding strategies creates new opportunities to mitigate stress caused by unpredictable weather patterns and seasonal variation. If a drought kills the spring honey flow, hives do not have to be moved, subjecting them to the stress of transport. Precision feed can bridge the gap until a late rain comes and the flow begins.

The management of variance in microclimates is another important area of opportunity for precision feed. Feed practice can compensate for areas with historically unpredictable or undesirable honey flow patterns. One specific example seen was the mitigation of microclimate toxins such as the California Buckeye. If foraged heavily, buckeye can have a detrimental effect on hive strength. And bloom timing is affected by weather. Some years, there is ample spring forage, and the bees have more to choose from, naturally diluting the effects. In other years, especially during drought, the buckeye might be the only bloom available, and toxins are more concentrated in honey. This can even kill off colonies entirely. This strategy could be similarly applied to pesticide or other environmental toxins. Incorporating such data into feed schedules offers a soft, more cost-effective solution to relocation.

The opportunities for precision feed in apiculture are real. Yet to realize them, precision feed must be practical. More research and technology solutions are needed to support the apiculturist to bring these benefits to the apiary. The precision feed cycle starts in the collection of timely, actionable data. Automated data such as weather, interior temperature, and weight can contribute to action models. It has also been shown that some data, such as hive audio, proved more difficult to translate to action. There is ample opportunity for more research into the types of data that can be collected, as well as research on the types of analysis that translates data into feed actions. For example, while personal experience with audio proved fruitless, there is evidence that audio data could be used to identify predatory attack [25]. If an attack was identified, there are several actions that might be taken such reducing feed amounts or installing entrance reducers and wasp traps. On further investigation, it may even be found to have an impact on feed strategy. For instance, feed equipment could be changed to discourage predation. Therefore, the careful study of predictive data such as this can be highly beneficial. It is likely that research using audio data in apiculture has “only grazed the surface of understanding their communication. There’s a lot more to be learned” [26].

Practical consideration is necessary for this knowledge to fully benefit apiculture. Therefore, these findings precipitate further research and development of technology in data collection to analysis methods and the facilitation and automation of feed actions themselves. Automated data collection and processing relieves labor and imprecision of manual processes. Further research in the types of remote sensors that can monitor and predict feed timing, quantity, and substance is a natural requirement. As the available data and diagnoses develop and become more rigorous, further research would be useful in the actionable policies such as identification of treatments, formulation of feed, and production of cultivation schedules. For example, a Precision Apiculture System (PAS) which monitored parameters such as temperature and honey production is able identify loss of productivity due to unexpected drops in temperature [27]. Results using this system conclude that “the data recorded by PAS platform provided a valid decisional support to the operator” [27]. Practice becomes more sophisticated as this knowledge can be linked to effective actions that improve health and productivity. There is a specific relationship between measurement and management [1]. Precision in the former is a necessary requirement for precision in the latter. Technologies that develop this precision in data acquisition and provide the decisional support and automation in subsequent cultivation action can manage costs and make precision feed accessible and economical for the common apiary.

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