Varroa treatment-free colony losses in the European honey bee (*Apis mellifera):* A review of published literature

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Key Words: Varroa, Varroa resistance, Varroa treatment-free, varroacides, biotechnical, honeybee.

Abstract

Varroa treatment-free beekeeping has been practiced for decades throughout Africa and Latin America and is becoming more popular in Europe and the USA. This type of management relies on the bees developing Varroa resistance, replacing the use of varroacides and biotechnical control methods. Many national and statutory bodies, for instance in the UK, Spain, France and Germany, advise or even legislate against Varroa treatment-free beekeeping. This review brings together published data on honey bee colony loss within the first five years of transition of colonies to Varroa treatment-free management. It also looks at long-term data on treatment free colony survival. In the transition phase, four types of strategy were identified of which two were particularly successful: 1. starting with known Varroa-resistant bees; or 2. starting with non-resistant bees and then selecting bees showing resistant traits, whilst mitigating losses with biotechnical methods in the first summer, followed by requeening in colonies with high Varroa counts. In both strategies, winter colony loss was 6-17% and was similar to control colonies (8-23%). Colony losses were higher (27-28%) if treatment was stopped in colonies without any mitigating strategies other than standard colony management, such as swarm capture or colony splits. If colonies were left untreated without any management, other than winter feeding, the majority died after three years, although up to 11 % of colonies survived five years. Once Varroa treatment-free apiaries were established, they have been shown to survive for twenty years or more. The advice given against treatment-free beekeeping therefore is misplaced.

Introduction

Varroa destructor is a widespread pathogen of the European honey bee that has caused significant honey bee colony loss, largely through the transmission of viral pathogens such as deformed wing virus (DWV) and acute bee paralysis virus (Locke et al, 2014; Martin et al, 2010; Oddie et al, 2023; Weaver et al, 2021). Varroa is commonly treated with chemical varroacides in many parts of the world including Europe and the US. However, a significant proportion of Varroa have developed resistance to the synthetic varroacides (Milani 1999, Thompson et al, 2002). Organic compounds such as oxalic acid, thymol, formic acid and lactic acid have been used successfully for the treatment of Varroa in many countries (Domatskaya & Domatsky 2020; Gregorc & Planinc, 2012; Hoppe et al, 1989; Jack & Ellis, 2021; Mutinelli et al, 1997; NBU 2024), and so far without Varroa developing resistance (NBU 2024). However, varroacides are not without their problems and additional cost. As well as the increasing and widespread Varroa resistance to synthetic varroacides being reported, their problems also include toxic effects on the honey bees themselves, leading to death of up to 10% of the worker bees and also loss of queens (Gregorc et al, 2018; Pietropaoli & Formato, 2019). Varroacides can also contaminate wax and honey, especially if used incorrectly (Chauzat & Faucon, 2007; Jiménez et al, 2005; The Honey Bee Health Coalition, 2021; Wallner, 1999;). As an alternative, or in addition to varroacides, biotechnical/husbandry techniques such as queen frame trapping, shook swarm, drone brood removal and colony splits can be used to decrease the Varroa load of colonies (British Columbia Ministry of Agriculture, 2024; Formato, 2020; NBU 2024; Manitoba agriculture, 2024; Ontario beekeepers, 2020), but these methods are only used by 15% of UK beekeepers (Valentine & Martin, 2023) although they are used by up to 50% of other European beekeepers, especially drone brood removal (Brodschneider et al, 2023). Biotechnical methods have variable efficacy but can be as effective as varroacides (Cengiz, 2018; Lodesani et al, 2019; Vercelli et al, 2023). However, biotechnical methods are not without their problems. Drone brood removal has generally a low efficacy and reduces the pool of drones for mating (Güneşdoğdu et al, 2021). The other biotechnical methods depend on generating a broodless period and thus reducing the colony size (Cengiz, 2018; Lodesani et al, 2019; Vercelli et al, 2023).

Bees have been found to have the ability to be resistant to Varroa due to mechanisms that relate to Varroa specific hygiene, which includes brood uncapping and recapping, and causes reduced Varroa fertility (Hawkins & Martin, 2021; Grindrod & Martin, 2021; Guichard et al, 2020; Locke et al, 2014; Martin 2022, Oddie et al, 2021; Panziera et al, 2017; van Alphen & Fernhout, 2020). This has been seen both in colonies bred in hives and long-lived wild colonies (DeMattos et al, 2016; Kruitwagen et al, 2017; Locke et al, 2014; Locke, 2016; Luis et al, 2022; Moro et al, 2021). This behaviour relates to increased sensitivity by the adult worker bees to mite infestations in the brood which may in turn be due to host brood characteristics that lead to altered volatile expression patterns (Scaramella et al, 2023). In addition to the recognition of resistance and as a reaction to the downsides and variable efficacies of Varroa treatment, many beekeepers have changed to Varroa treatment-free beekeeping. Varroa treatment-free bee keeping is defined as keeping bees without the use of varroacides or biotechnical methods, in order to artificially control the mite population (Heaf, 2021a). The COLOSS multi-country survey of Varroa treatment and colony loss showed that in Wales, Greece, Norway, Netherlands and Ireland 2030% of beekeepers did not use any Varroa control methods (Brodschneider et al, 2023). In the United States, studies have shown that up to 31% of beekeepers did not use varroacides and up to 20% used no Varroa control at all (Haber et al, 2019). A recent survey of UK beekeepers showed that 28% had not used varroacides in the last year and 6% had not treated with a varroacide for more than five years (Valentine & Martin, 2023).

There are several barriers to beekeepers wishing to change to treatment-free beekeeping. These include national legislation to enforce treatment with varroacides in countries such as Spain, France and Germany and the advice against stopping varroacides from statutory organisations such as the UK National Bee Unit (NBU) (Jack & Ellis, 2021; LeConte et al, 2010; Ministeriode Agricultura Pescay Alimentacion, 2019; National Bee Unit, 2024). Using the NBU advice as an example, the perceived problems with not using varroacides include the level of loss of colonies, especially in the early transition phase, the difficulties in breeding resistant colonies from unselected drones (i.e. the need for mating control when breeding for a trait such as resistance), the lack of commercially available Varroa- resistant strains and the perceived need for treatment-free colonies to be geographically isolated from treated colonies (NBU 2024). However, there are numerous beekeepers who report that they have been treatment-free for a decade or more. which contradicts most of the perceived barriers listed above (Hudson & Hudson, 2022; Kefuss et al, 2015; Kruitwagen et al, 2017; Le Conte et al, 2007; McMullan, 2018; Oddie et al, 2017; Requier et al, 2024; Rodriguez et al, 2022; Osterlund, 2020; Oxfordshire Natural Beekeeping Group, 2024). It is likely that the perception of early colony loss is still a barrier to beekeeper operations making the change to treatment-free. To see if the concerns about stopping varroacides are valid and whether fears of early colony loss are well founded, this article reviews the literature to identify published early colony loss data in beekeepers transitioning to Varroa treatment-free beekeeping and the subsequent long-term performance of treatment-free apiaries.

Methods

Literature review

The following publication databases were searched: Google Scholar, Google, PLOS, BiomedCentral and bioRxiv. Search terms included, 'Varroa', 'Varroa resistance', 'treatment free beekeeping',' honey bee colony loss',' Varroa treatment'. Titles of articles that were appropriate then had their abstract read and then the full text article read, if promising. Books on treatmentfree beekeeping were also obtained. All finalised articles and books also had their reference list reviewed to identify any further suitable references. Also, credible data from sources other than books and scientific journals were identified and included in the final analysis as appropriate.

Data Included

Any reported data on early colony loss was included if it was recorded over a minimum of three years with the first year being the start of a transition from Varroa treatment to treatment-free beekeeping. Information was gathered about number of colonies, source and type of the bees, any Varroa management interventions used over the transition period and any colony loss data recorded for comparison (control) bee colonies that received Varroa treatment. Long-term colony survival data was included for colonies that had been Varroa treatment-free for six years or more.

Results

Eleven publications met the inclusion criteria of having colony loss data recorded for at least three years, during which varroacide treatment was not used and any biotechnical Varroa treatments applied were used as a temporary means of transition to complete treatment-free management.

Survival of un-managed colonies

On the basis of the methods used in the selected publications, two general types of study were identified. The first type consists of studies specifically looking at the effect of Varroa on the bees. In these, non-resistant bees were left largely unmanaged apart from some autumn feeding of syrup (Type 1 studies). This has been called the 'Bond Method' (Live and let die) (Fries et al 2006; Kefuss et al, 2004). These studies were performed either to look at the ability of unmanaged colonies to survive (Fries et al, 2006; Kefuss et al, 2004; Nordström et al, 1999) or to look at the mechanisms that lead to Varroa-related colony loss (Martin et al, 1998; Martin et al, 2010). These studies were generally small, with numbers of colonies involved being less than twenty, apart from the Fries research that included 150 colonies (Table 1).

Table 1: Type 1 studies in which non-resistant bees were left largely unmanaged

Reference	Country	Type of bee	Number of colonies at start of transition period	Colony loss in year 1	Colony loss in year 2	Colony loss in year 3	Colony loss in year 4	Colony loss in year 5	Number of colonies surviving at end of 5 years	Average annual colony loss for first 3 years	Average annual colony loss for first 5 years
Martin et al, 1998	England	*A. mellifera*	8	50%	25%	100%			0	33%	-
Nordström et al. 1999	Sweden	*A. mellifera*	7	-	88%[a]	-	-	-	-	-	-
Nordström et al. 1999	Denmark	*A. mellifera*	5	-	100%	-	-	-	0	-	-
Fries et al, 2006	Sweden	*A. mellifera* locally bred	150[b]	5%	40%	76%	57%	19%	11[c]	31%	32%
Martin et al, 2010	England	*A. mellifera*	20	95%	100%	-			0	-	-
Kefuss et al, 2004	France	*A. mellifera carnica*	9	89%	0	0	0	0	1	30%	18%

[a]Data given for 2 years only, [b] Colonies artifically infected with Varroa, [c] Includes 5 swarm colonies arising from the original colonies.

In two of the six Type 1 studies, all colonies were dead after two years (Nordström et al, 1999) (Denmark), Martin et al, 2010)(UK). In a third study, all colonies had died after three years (Martin et al, 1998) (UK). One of the studies only gave results for two years with an 88% loss by then (Nordström et al, 1999) (Sweden). In the remaining two of the six studies, a small proportion of colonies (7-11%) survived for five years or more (Fries et al, 2006; Kefuss et al, 2004), albeit that the Fries study did allow reintegration of a few swarm colonies into the study population.

Survival of colonies transitioning to Varroa treatment-free status

The second group of studies consists of observational data of colony loss during the transition to treatment-free beekeeping of managed colonies (Type 2 studies) (Table 2). Type 2 studies were divided into three different strategies: Strategy A - starting colonies had no known resistance and received no Varroa treatment from year one; Strategy B - starting colonies had no known resistance but received temporary biotechnical Varroa treatment before the first winter if the Varroa count was high, followed by re-queening from colonies with naturally low Varroa counts in the following spring, until treatment-free was achieved; Strategy C - starting colonies had known resistance traits and received no Varroa treatment from year one.

The Strategy A studies (Seeley, 2020; Heaf 2021b) are different to Type 1 studies listed above, in that although they are of non-resistant bee colonies which received no Varroa treatment, they were otherwise managed along conventional lines. These results are complex, in that as in normal beekeeping, the apiaries were being supplemented through swarms, splits and possible external additions. However, the results are consistent, with 27-28% winter colony losses which is higher than the control colonies, (18%) but not excessively so, when compared to losses seen for all beekeepers in the COLOSS study (7-36%) (Gray et al, 2022).

There is only one example of Strategy B management included here (Riley, 2024; Westerham beekeepers, 2024). This strategy involves starting with non-resistant bees and then using a variety of methods to identify Varroa resistance over the transition period. This includes frequent monitoring of Varroa levels and hygienic behaviour within the colonies throughout the year. Temporary reduction of Varroa levels is achieved through biotechnical methods (shook swarm or queen frame trapping) for colonies with high Varroa levels before the first winter, followed by re-queening in the following spring from colonies with naturally low varroa counts, until all colonies show Varroa-resistant abilities with constant low Varroa levels (ideally a mite drop of <5/day). Again, the results are complicated by changing colony numbers through splits and own-swarm collection, but overall the winter colony losses over the five years, averaging 17%, are lower than the regional average of 23%.

Table 2: Type 2 studies using observational data of the early transition years for colonies being managed towards Varroa treatment-free status

Reference	Country	Type of bee	Type of Transition (see main text)	Starting bees from Varroaresistant stock (Yes/No)	Biotechnical methods used, as necessary in first year of transition (Yes/No)	Number of colonies at start of transition period	Average winter colony loss for first 3 years	Number of colonies at end of 5 year transition period	Average winter colony loss for first 5 years	Average winter loss from control (treated) colonies
Heaf , 2021b	Wales	*A. mellifera* locally bred	Strategy A	No	No	2	7%	27	27%	18%[b]
Seeley, 2020	USA	*A. mellifera* swarms from feral bees	Strategy A	Unknown	No	16	28%e	-	-	-
Riley, 2024; Westerham beekeepers, 2024	England	*A. mellifera* locally bred	Strategy B	No	Yes	28	17%a	45	17%[a]	23%[b]
Hudson & Hudson; 2016; Heaf, 2021b	Wales	*A. mellifera* locally bred	Strategy C	Yes	No	27	19%	403	13%	19%[c]
LeConte et al, 2007	France	*A. mellifera* locally bred	Strategy C	Yes	No	82	11%	40	13%	8%[d]
Kefuss et al, 2004	France	*A. mellifera intermissa*[f]	Strategy C	Yes	No	9	7%	6	6%	-

[a] Colony loss averaged over the 5 years in the reported colony loss data [b] Southern England results of British Beekeepers Association annual winter colony loss survey. [c] Control survey of local beekeepers who treated for Varroa [d] 80 local varroacide-treated control colonies [e] 3 years of data only provided, [f] This is an African (Algerian) sub-species, but the study was in France and the bees quickly hybridised with local bees.

Three Strategy C-type studies met the inclusion criteria. All have the characteristic of having started out with acquired colonies that were already showing resistant traits. In the cases of Hudson (Heaf 2021a) and LeConte et al (2007), the starting bees were acquired mostly from beekeepers who had bred Varroa-resistant bees locally, although in the case of the Hudson study this also included some collected swarms from long-lived wild colonies (Hudson & Hudson, 2016; Heaf 2021a; LeConte et al, 2007). In the Kefuss (2004) study the starting Varroaresistant bees were an Algerian sub-species (*A. mellifera intermissa)* although these quickly hybridised with local bees. Average winter colony losses across the three studies were

6-13% which was the same, or lower, than control colony losses (8-19%) Similarities and differences between the studies in Tables 1 and 2

The eleven studies reported in tables 1 and 2 were all similar in that they followed defined bee colonies for defined periods of time and reported colony loss, but there were differences that should be noted which made direct comparisons between studies more difficult.

The Type 1 studies in table 1 are most uniform and therefore most directly comparable. All reported the same identified colonies throughout, apart from the Fries study where the final results were affected by a small number of swarms that occupied empty hives. However, the effect was small, as the swarms comprised only a few percent of the initial 150 colonies.

The type 2 studies whose results are shown in table 2 are different to those in table 1 in that in common with 'real-life' beekeeping, colonies were being added as well as lost in the studies. The differences between individual type 2 studies are accounted for in this review, to some degree, by sub-dividing type 2 studies into strategies A, B and C which show the same approach to Varroa treatment-free transition.

Long-term survival of Varroa treatment-free colonies

Table 3 gives long-term colony loss results for managed, treatment-free colonies where results are available for six years or more (Hudson & Hudson, 2022; Kefuss et al, 2015; Kruitwagen et al, 2017; Le Conte et al, 2007; McMullan, 2018; Oddie et al, 2017; Requier et al, 2024; Rodriguez et al, 2022; Osterlund, 2020; Oxfordshire Natural Beekeeping Group, 2024). Numbers of colonies varied greatly across the studies from 70-220,000 and the number of years since Varroa treatment was stopped ranged from nine to twenty four years. They were also widely spread geographically from the tropical climate of Cuba to the colder Northern European climate of Norway. There wasn't any appreciable winter broodless periods in Cuba, unlike the countries in which the other studies were performed which had cold winters. Therefore, winter colony losses weren't an appropriate measure for Cuba and so annual colony losses is the measure used. The colonies in each study were all showing Varroa-resistant traits, but the route taken to achieve this for each study was different. The other difference for Cuba was that year-round laying by the queen meant that queens were routinely replaced each year (Requier et al, 2024; Rodriguez et al, 2022). The winter/annual losses ranged from 10-19% for all studies except one. These losses were the same or lower than are reported for Varroa-treated bee colonies (7-36%)(Gray et al, 2022; Requier et al, 2024). The Oxfordshire Beekeepers winter losses were an outlier at 34% winter losses, although previously had averaged 29% (Oxfordshire Natural Beekeeping Group, 2024). In their report they explained this difference by one member of their group importing nonresistant bees into their apiary. It is also worth noting that this group practices 'Natural Beekeeping' in which the bees are kept in top-bar hives and colony reproduction is through swarm collection and bait hives, but not splits or artificial swarms (Natural Beekeeping Trust, 2024). The other studies of long-term Varroa treatment-free outcomes were for bees kept in box hives of various types with management strategies that often included swarm control, splits and re-queening using resistant queens, usually self-bred.

Table 3: Examples of long-term Varroa treatment-free management outcomes

Reference	Country	Number of colonies at end of observation period	Years since last Varroa treatment	Most recent annual/winter colony loss data[a]
Rodriguez et al, 2022; Requier et al, 2024	Cuba	220,000	20	19%
McMullan, 2018; Hudson & Hudson, 2022	Ireland	10	12	11%
Hudson & Hudson, 2022	Wales	467	13	13%
Le Conte et al, 2007	France	37	11	12%
Kefuss et al, 2015	France	519	14	'low'[b]
Oddie et al, 2017; Osterlund, 2020	Norway	1500	24	10%
Kruitwagen et al, 2017	Netherlands	70	9	18%
Oxfordshire Natural Beekeeping Group, 2024	England	167	9[c]	34%[d]

[a] Mostly winter colony loss data but some studies only gave annual loss data, [b] Described as having low Varroa levels and colonies being used for commercial beekeeping, [c] 9 years from start of data collection period but the colonies have been Varroa treatment-free for much longer, [d] The average colony loss over the previous five years was 29%

Discussion

These results show that it is possible to successfully establish honey bee colonies that can be managed Varroa treatment-free within a transition period of five years or less, depending on the strategy used in the transition phase. There were two highly successful strategies for stopping Varroa treatment and switching to Varroa treatment-free that had similar success.

The first successful strategy is to start with locally-bred Varroa-resistant bees either acquired from other beekeepers or as swarms taken from long-lived wild colonies (Strategy Type C). In all cases reported here, colony loss was similar, or lower, than colony loss in control colonies treated with varroacides and averaged less than 20% winter losses (Heaf, 2021a; Hudson & Hudson, 2016; Kefuss et al, 2004; Le Conte et al, 2007).

The other successful strategy (Strategy Type B) was to phase out Varroa management, by using biotechnical treatment methods as interim Varroa mitigation before the first winter, such as shook swarm, queen frame trapping and drone brood removal, followed by queen replacement in those colonies with high Varroa levels. Again, the reported winter colony losses were less than 20% both in the early transition phase and beyond (Riley, 2024; Westerham beekeepers, 2024).

The alternative strategies for moving away from varroacide treatment had much higher colony loss results. These both involved starting with bees that were not known to be Varroa resistant and stopping varroacide treatment without any mitigating transitional Varroa management methods. When this was done as part of research into colony survival with minimal intervention for the colonies, other than winter feeding, as was used in the Swedish 'Bond' (Live and let die) study (Fries et al, 2006), then between ninety and a hundred percent of the colonies die within three years (Kefuss et al, 2004; Martin et al, 1998; Martin et al, 2010; Nordström et al, 1999 (Sweden); Nordström et al, 1999 (Denmark)). When the strategy of stopping treatment in nonresistant bees was used in colonies that were being managed with a higher level of intervention, such as colony replacement with recaptured swarms, swarm management and colony splits (Strategy Type A), the average winter colony loss was 27-28% (Heaf 2021b; Seeley, 2020). This colony loss is higher than that seen with the Type B and Type C strategies, but much lower than seen with the research colonies subjected to the Bond-type strategy.

Once the colonies had been treatment-free for more than five years, then the published studies show winter/annual colony loss rates of mostly <20% and as low as 11% in apiaries that had been treatment free for up to 20 years (Hudson & Hudson, 2022; Kefuss et al, 2015; Kruitwagen et al, 2017; Le Conte et al, 2007; McMullan, 2018; Oddie et al, 2017; Requier et al, 2024; Rodriguez et al, 2022; Osterlund, 2020). The one exception is from a Natural Beekeeping group who also included data from some colonies that had only recently started transitioning to treatment free (Oxfordshire Natural Beekeeping Group, 2024).

A note of caution has to added for the interpretation of these studies. The type 1 studies of largely-unmanaged colonies were all part of research studies and as such were uniform in their approach. There were a starting number colonies whose survival was monitored without any mitigating interventions, other than winter feeding and a few additional swarms added in one study. Therefore type 1 study results were directly comparable. However, there was a lot more heterogeneity in the type 2 studies of managed transition to Varroa treatment-free beekeeping. These differences were accounted for to some degree in this review by reporting the results according to three different management strategies. The type 2 studies were not part of formal prospective scientific research projects. As such colony numbers varied season by season, due to replacement and additions from splits, swarm collections and other additions. The results are therefore of individual management strategies in a fluid number of colonies with the constant reference point of winter survival. What these studies do though, is reflect real-life beekeeping.

Most official Varroa management guidelines still advocate for chemical treatment for Varroa (British Columbia Ministry of Agriculture 2024; Formato 2020 ; Jack & Ellis, 2021; LeConte et al, 2010; Manitoba agriculture 2024; Ministeriode Agricultura Pescay Alimentacion, 2019; National Bee Unit, 2024; Ontario beekeepers, 2020) and in some, such as the UK National Bee Unit, go as far as to strongly advise against managing bees Varroa treatment-free (National Bee Unit, 2024). Advice against stopping Varroa treatment is based on three basic arguments: that bee colonies die out quickly without treatment, that there are no widely available Varroa-resistant honey bee strains (apart from in the US) and that resistant colonies need to be geographically isolated from non-resistant colonies to prevent dilution of the resistance gene pool by mating of queens with unselected drones from non-resistant colonies (National Bee Unit, 2024; Perfect Bee, 2024). This review shows that these arguments appear to be misplaced.

With regards to the first argument concerning early large-scale colony loss, whilst it is true that if the Bond-type, live and let die method where to be used in the transition phase to treatmentfree beekeeping, and that colonies are not refreshed and replaced by swarms and splits, then early colony losses would be very high (Fries et al,2006; Kefuss et al, 2004; Martin et al, 1998; Martin et al, 2010; Nordström et al, 1999 (Sweden); Nordström, et al 1999 (Denmark)) Even so, in some studies 7-11% of colonies survived long term (Fries et al,2006; Kefuss et al, 2004). However, most beekeepers will continually refresh the apiary with re-captured swarms and splits under which circumstances the apiary average winter colony loss was only 27-28% (Heaf, 2021b; Seeley, 2020) which is similar to winter losses in beekeepers who treat with varroacides (Gray et al, 2022; Steinhauer et al, 2023). The conservative advice by national bodies to continue using varroacides is probably given with regards to perceived implementation barriers to treatment-free management for larger-scale beekeepers where the aim is to maintain individual colonies long-term, maximise honey production and reduce swarming by annual/biannual re-queening (Buchler et al, 2023). However, these barriers to going treatmentfree are not necessarily significant, as for instance, annual requeening of Varroa-resistant colonies has been shown to be both possible and successful in Cuba (Rodriguez et al, 2022). It has also been shown that commercial beekeeping of treatment-free bees is practiced, with enterprises consisting of up to 1600 treatment-free self-bred colonies (Guichard et al, 2023; Kefuss et al, 2015; LeConte,2020; The Honey Bee Health Coalition, 2021).

The second argument against treatment-free beekeeping is that there are no widely available Varroa-resistant honey bee strains, which is presumably seen as a barrier to commercial bee keeping. The lack of commercially available Varroa-resistant strains is generally true in the UK and many other European countries (Buechler et al, 2022; Kefuss et al, 2015; Le Conte et al, 2020), although Varroa-resistant strains, such as Russian hybrid bees, Varroa Sensitive Hygiene bees and the Minnesota Hygienic line are available in the United States (Kefuss et al, 2015). Varroa-resistant strains are also available in Cuba (Requier et al, 2024; Rodriguez et al, 2022). In addition, there are many locally-available Varroa-resistant bees across Europe including the UK (Buechler et al, 2022; Heaf, 2021a; Hudson & Hudson, 2016; Kefuss et al, 2015; Le Conte et al, 2020; Riley, 2024) and research shows that commercial beekeeping is sustainable using breeding programmes by the beekeepers themselves (Kefuss et al, 2015; Le Conte et al, 2020; The Honey Bee Health Coalition, 2021). It has also been said that Varroa-resistant bees produce less honey (Mertz 2021), although commercial beekeepers who are treatment-free would dispute this (Kefuss et al, 2015; Le Conte et al, 2020; The Honey Bee Health Coalition, 2021) and there is evidence from Cuba and Latin America that honey production has increased 'despite' treatment free beekeeping. (Rodriguez et al, 2022).

The third argument that has been used against treatment-free bee keeping is that resistance can't be maintained unless the colonies are geographically isolated, as unselected mating with drones will dilute the resistance gene pool. However, there are numerous examples of beekeepers maintaining their own resistant bees long-term despite their apiaries being surrounded by beekeepers who continue to treat with regular varroacides (Buechler et al,2022; Kefuss et al, 2015; Kruitwagen et al, 2017; Le Conte et al. 2007; Le Conte et al, 2020; Oddie et al, 2017; Osterlund, 2020; Oxfordshire Natural Beekeeping Group, 2024; The Honey Bee Health Coalition, 2021). How can that be explained? The mechanisms of Varroa resistance in honey bees have been well studied and the important traits in the honey bee seem to be uncapping/recapping and brood removal which leads to reduced mite reproduction and reduced viral load of other pathogens such as DWV (Grindrod & Martin, 2021; Guichard et al, 2020; Hawkins & Martin, 2021; Martin, 2022; Oddie et al, 2021; van Alphen & Frernhout, 2020). The genetics of resistance are also beginning to be understood (Lefebre et al, 2024; Martin et al, 2024; Mondet et al, 2020). Varroa-resistant behaviour in worker bees is inherited from the queen and is not a learned behaviour (Martin et al, 2024). So how can Varroa resistance persist longterm if the queens are mating with unselected drones, as seems to be the case for the examples given above where resistance persists despite lack of geographical isolation? (Buechler et al, 2022; Kefuss et al, 2015; Kruitwagen et al, 2017; Le Conte et al, 2007; Le Conte et al, 2020;
Oddie et al, 2017; Osterlund, 2020; Oxfordshire Natural Beekeeping Group, 2024, The Honey Bee Health Coalition, 2021; Valentine & Martin, 2023). The answer may be that the genetics of resistance is not governed by simple Mendelian inheritance, but more complex genetic

interactions might be in play, such as epigenetic and epistatic interaction phenomena (Alhosin, 2023; Conlon et al, 2018; Martin et al, 2024). In epigenetics, the activity of a gene can be switched on or off by environmental factors (such as is seen when female bees becoming queens due to a royal jelly diet) and so a gene's phenotypic expression (such as for resistance) may not be dependant on inheritance from the drone (Alhosin, 2023; Martin et al, 2024). In epistatic interactions, multiple genes for a phenotype, such as Varroa resistance, might interact in complex ways by enhancing or reducing phenotypic expression (Conlonet al, 2018).

Possible confounding factors in this review.

It is possible that there are other studies that might have been included but were not found using the search criteria used in this review. There is also a possibility of publication bias in which studies with negative outcomes were not published. This seems less likely as this review found a range of outcomes with no obvious predominance of positive outcomes.

Conclusions

This review shows that honey bee colonies that do not require Varroa treatment can be established within five years or less of stopping established Varroa treatment. Once Varroa treatment-free apiaries are established, they can be continued treatment-free long-term, for twenty years or more. Treatment-free, Varroa-resistant colonies can be maintained even in areas where surrounding colonies do not have Varroa resistance and can be used successfully in large-scale commercial bee keeping enterprises.

Acknowledgements

I would like to acknowledge Professor Stephen Martin and Steve Riley for commenting on a draft of the paper.

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