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ORIGINAL ARTICLE

Integrated pest management against *Varroa destructor* reduces colony mite levels and delays treatment threshold

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SUMMARY

Two independent, long-term (17 months and 87 weeks) studies were done to appraise the effects of published integrated pest management (IPM) practices on colony varroa mite levels, length of time before onset of treatment threshold, and other measures of colony productivity. Screen hive floors tended to reduce colony mite levels (24-h sticky sheet counts), sometimes significantly. Likewise, mite-resistant queens tended to cause a numeric and sometimes significant reduction in mite levels; number of mites on sticky sheets decreased as the percentage expression of hygienic behaviour in a colony increased, and on the majority of sampling episodes the number of mites retrieved on sticky sheets was numerically lower in colonies with queens expressing suppressed mite reproduction (SMR). In six of eight cases when IPM components were found to interact they did so in a manner favourable to mite control. Time until achieving treatment threshold was significantly delayed in colonies with SMR queens (*c.* 72 weeks) compared to non-selected queens (59). In one experiment, stored honey was significantly reduced in colonies with screens (3.8 frames) compared to solid floors (5.1); likewise, stored pollen was lower in screen colonies (0.9 frames) than on solid floors (1.3). SMR queens tended to have reduced brood production.

Keywords: integrated pest management, IPM, *Apis mellifera*, *Varroa destructor*

INTRODUCTION

One of the explicit goals of investigators in the integrated pest management (IPM) of *Varroa destructor* is to reduce or eliminate beekeepers' reliance on synthetic acaricides. Several non-chemical strategies have shown promise as control agents, either by (1) eliminating mites from a colony, or (2) slowing rate of mite population growth. Examples of the former include grooming behaviour in bees (Peng, 1992), various brood trapping techniques (Dung *et al*., 1995; Schulz *et al*., 1983), and dusts applied in the hive (Fakhimzadeh, 2000). Examples of the latter are weighted toward honey bee stocks that display genetic varroa resistance (Spivak, 1996; Harbo & Harris, 1999; Harbo & Hoopingarner, 1997; Rinderer *et al*., 1997), but also include apiary isolation (Sakofski *et al*., 1990), apiary exposure to sun (Rinderer *et al*., 2004) and screen hive floors that reduce colony mite levels (Pettis & Shimanuki, 1999), apparently by decreasing the rate at which foundress mites invade brood cells (Harbo & Harris, 2004).

In spite of the promising IPM tools suggested by the literature, large-scale adoption of IPM has not been realized in many parts of the world. Few of the practices listed above can singly or indefinitely keep mites at non-damaging levels; computer modelling simulations indicate that non-chemical IPM practices delay damaging mite levels rather than prevent them (Hoopingarner, 2001; Wilkinson *et al*., 2001). Thus at this point it seems most practical to think of IPM as a means to delay, not eliminate, chemical treatment. If a beekeeper can prolong the inter-treatment interval as long as possible this not only reduces net chemical use and its attendant hazards to bees, honey and the environment, but enables mites through genetic recombination and reproduction over time to conserve their chemical susceptible genes (see Metcalf, 1982), thus prolonging the useful life of an acaricide.

If delaying chemical applications is a key objective of IPM then it is paramount that beekeepers have the means to monitor mite population growth and criteria to determine when mites have achieved levels that warrant chemical treatment. Such treatment thresholds have been developed in the USA, specifically for the south-east (Georgia and South Carolina) and north-west (Washington State). On the basis of 24-h mite counts on hive floor sticky sheets, recommended early season treatment thresholds for the two regions are congruent at 12 mites for the north-west (Strange & Sheppard, 2001) and 0.7–12.2 mites for the south-east (Delaplane & Hood, 1997, 1999) for April and February, respectively. For August the recommendations are more divergent at 23 mites for the north-west and 70.8–224.4 for the south-east. Armed with such region-specific thresholds, coupled with known or suspected methods of slowing mite growth, beekeepers are now within reach of a comprehensive IPM paradigm for managing varroa. It remains to experimentally demonstrate whether the diverse and published IPM tactics do indeed delay onset of treatment threshold. Such a project is essentially a confirmation of decades of work by numerous researchers and signals the maturity of IPM research on this important beekeeping pest.

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In this study we tested the efficacy of three IPM practices – genetically mite-resistant bees, screened hive floors, and apiary isolation – at slowing growth of colony mite populations, delaying onset of treatment threshold, and improving colony health conditions. Two independent experiments are herein reported: one using hygienic-selected queens as the resistant stock and another, using queens selected for suppressed mite reproduction (SMR (Harbo & Harris, 1999), lately understood to be a specified form of hygienic behaviour (Ibrahim & Spivak, 2004; Harbo & Harris, 2006)).

MATERIALS AND METHODS

Effects of hygienic queens, screens and isolation

In June–July 2001 40 colonies of *Apis mellifera* were set up in north Georgia (USA), each with *c.* 0.9 kg bees, one Langstroth hive body, a queen excluder, and one super of honey for food. Small incipient populations of *V. destructor* were achieved by collecting experimental bees from an apiary in which overnight mite counts on hive floor sticky sheets averaged 0.4 ± 0.5 (mean ± s.d.). Queens were marked and replaced as necessary and colonies managed as for honey production except for experimental constraints explained below.

Twenty of the colonies were randomly assigned to one of three 'isolated' apiaries and 20 to three 'non-isolated' apiaries. There were three apiaries of each class, two with eight colonies each and one with four. Within each apiary, each colony randomly received one of the following experimental treatments: (1) a queen selected for hygienic behaviour, conventional solid hive floor, (2) hygienic queen, screen floor, (3) non-selected queen, solid floor, or (4) non-selected queen, screen floor. Treatments were replicated twice in those apiaries with eight colonies. 'Isolated' apiary sites were selected on the criterion that each was at least 5 km from another known apiary. 'Non-isolated' apiaries were apiaries owned by beekeeper co-operators; experimental colonies were simply placed among non-experimental ones, and co-operators were free to manage their own colonies as they wished. Production-grade hygienic queens (Spivak, 1996) were purchased from a queen supplier, and screen floors were the type described by Pettis & Shimanuki (1999) in which a screen is suspended above a conventional solid hive floor.

Beginning 8 August 2001 and continuing at monthly intervals until November 2002 (inclusive), colonies were sampled for the number of mites collected on overnight (*c.* 24 h) hive floor sticky sheets and the number of months determined at which each colony remained under the minimum treatment threshold of 60 mites (Delaplane & Hood, 1999). Since sticky sheets necessarily rest on the hive floor while they are in place, any benefit from screened floors is presumably suspended during that interval; however in this experiment (and the next) this effect was experimentally void because all colonies were treated identically. A colony was removed from further monthly sampling once it achieved minimum treatment threshold at which time it received a rescue application of acaricide Api-Life VAR (Chemicals LAIF) or formic acid after the gel formulation of Feldlaufer *et al.* (1997) in plastic containers 55 mm deep, 85 mm diameter, 300 ml volume); the miticide applications not only salvaged colonies but minimized mite emigration within apiary, thus maintaining independence of observations. In April, September and November 2002, we collected data on gross colony condition by summing for each surviving colony the amount of adult bees, brood (including eggs), honey and pollen using the proportion of a whole deep frame as units (after Skinner *et al.* 2001). Frames of adult bees were converted to estimates of colony bee populations with the regression model of Burgett & Burikam (1985), and frames of brood converted to cm^2 brood based on the determination that surface of both sides of a deep frame (comb) is 1754 cm^2. On two occasions (June and September 2002) we measured hygienic behaviour of each colony using the liquid nitrogen method of Spivak & Reuter (1998).

The effects of apiary isolation, queen type (hygienic or non-selected), and hive floor type (solid or screen) on mite numbers retrieved on overnight hive floor sticky sheets (as well as colony strength parameters for April, September and November 2002) were tested with analysis of variance recognizing apiary (isolation class), month, and all interactions of main effects with apiary and month (Proc GLM, SAS 1992). When this analysis showed interactions between month and main effects the analyses were run separately by month. Additionally, the degree of hygienic expression by colonies was used as a covariate in an analysis of variance for the June 2002 mite numbers; when this test failed to show effects of hygienic behaviour on mite numbers we ran regression analyses for the June and September 2002 data testing for a linear, quadratic, or cubic relationship between percentage expression of hygienic behaviour and mite numbers on overnight sticky sheets. Only linear relationships were confirmed and presented below.

Effects of SMR queens, screens and isolation

The basic design and execution described above was repeated in 2002–2003 with the following changes. The experiment was set up with 40 overwintered, rather than package, colonies beginning in March 2002. Since the colonies available to us were headed by a mixture of non-selected queens and queens selected for SMR, we attempted to equalize incipient varroa levels by starting each colony with two frames of brood and bees from a non-selected queen and two frames of brood and bees from an SMR queen. Screen hive floors (Brushy Mountain Bee Farm, Moravian Falls, NC) consisted of a floor of screen mesh (3.2 mm) open to the ground below.

Instead of hygienic queens, for our resistant treatment we began with instrumentally-inseminated queens selected for SMR purchased from a commercial breeder. Over the course of the study many of these queens died, to the extent that we decided to continue the study with naturally-mated daughters of these queens. To help control for this variation, in May and July 2003 we measured expression of SMR for each colony (personal communication, Jeff Harris, US Dept Agric) for use as a covariate in subsequent ANOVA. Twenty to 500 cells (depending on availability of brood) of white/purple-eyed to tan-coloured pupae were excised from their cells and the cell contents examined for presence and demographic characterization of mite families. Cells were discarded if they contained evidence of >1 foundress. A foundress was deemed non-reproductive if by the white/purple-eyed bee stage she had produced no living brood at or beyond the protonymph stage, or if by the tan pupa stage she had produced no living brood at or beyond the deutonymph stage. Average expression of suppressed mite reproduction (percentage of mite families non-reproducing) was 12.9 ± 3.3, n = 16 (mean ± s.e.) for SMR queens and 8.8 ± 3.2, n = 10 for non-selected queens. SMR was shown to be a non-significant covariate in ANOVAs.

Beginning 7 May 2002 and continuing every three weeks until 12 November 2002 (inclusive), then again from 25 March 2003 until 2 December 2003 (inclusive), colonies were sampled for the number of mites collected on 3-day hive floor sticky sheets; numbers were converted to a 24-h basis to facilitate comparison with other data sets. The number of weeks was noted at which each colony remained under the minimum treatment threshold of 60 mites (Delaplane & Hood, 1999). Beginning 28 May 2002 and repeating at 6-week intervals until 13 November 2003 (inclusive), and again from 18 March 2003 until 30 July 2003 (inclusive, one time a 7-week interval), we collected data on gross colony condition.

RESULTS

Effects of hygienic queens, screens and isolation

For average number of varroa mites, the full model analysis detected significant effects only for floor type (F = 8.4; df = 1,12;

TABLE 1. Average monthly values (± s.e.) for number of mites retrieved on 24-h mite monitoring sticky sheets for colonies on conventional solid hive floors or screen floors. Numbers in parentheses = *n*. For the months of June and July 2002 (*) mite levels were significantly lower in colonies with screen floors.

Month	Solid floor	Screen floor
Aug 2001	1.0 ± 0.3 (20)	0.7 ± 0.2 (19)
Sep 2001	2.0 ± 0.4 (20)	2.2 ± 0.5 (20)
Oct 2001	6.2 ± 1.7 (19)	5.3 ± 1.1 (20)
Nov 2001	12.1 ± 3.3 (18)	10.1 ± 2.5 (20)
Dec 2001	11.1 ± 3.0 (18)	7.2 ± 1.9 (20)
Jan 2002	6.9 ± 2.8 (19)	2.8 ± 0.8 (20)
Feb 2002	6.2 ± 1.4 (13)	8.9 ± 3.2 (17)
Mar 2002	13.4 ± 4.2 (13)	10.9 ± 3.8 (15)
Apr 2002	23.8 ± 7.3 (13)	22.1 ± 5.7 (16)
May 2002	34.5 ± 16.1 (13)	10.1 ± 3.0 (16)
Jun 2002	42.1 ± 11.2 (11)	15.3 ± 3.7 (14)*
Jul 2002	148.7 ± 30.5 (11)	59.8 ± 8.7 (14)*
Aug 2002	12.5 ± 9.5 (2)	32.6 ± 11.4 (8)
Sep 2002	47.5 ± 44.5 (2)	34.8 ± 11.2 (6)
Oct 2002	0	7.7 ± 2.9 (5)
Nov 2002	0	5.2 ± 2.7 (5)

$P = 0.0134$). Across the 16 sampling months (spanning 17), the average number of varroa mites retrieved on 24-h sticky sheets was lower in colonies with screen floors (12.7 ± 1.3, $n = 235$, mean ± s.e.) than with conventional solid floors (20.4 ± 3.3, $n = 194$). However, because of many interactions we also ran analyses by month. On 11 of 16 months, the average number of varroa mites retrieved on 24-h sticky sheets was numerically lower in colonies with screen floors. On two of those months, June and July 2002, mite numbers were significantly reduced in colonies with screen floors ($F \geq 6.5$; df = 1,6; $P \leq 0.043$) (table 1). Interactions between main effects were detected for apiary isolation and floor type on months 10 and 13 ($F \geq 5.7$; df = 1,6; $P \leq 0.0536$). On the two months we measured hygienic behaviour, the relationship between number of mites retrieved on 24-h sticky sheets and percentage hygienic expression was explained by regression models with negative linear terms (figs 1 and 2).

Time before achieving treatment threshold (months) was not significantly affected by any independent variable. Mean months to threshold was 13.4 ± 0.7 months (mean ± s.e., $n = 16$) for colonies with screen floors, 11.6 ± 0.5 ($n = 14$) for colonies with solid floors, 11.9 ± 0.6 ($n = 16$) for hygienic queens, and 13.4 ± 0.7, ($n = 14$) for non-selected queens.

Concerning the three months for which we measured gross colony condition, the full model ANOVAs failed to detect differences among independent variables for any parameter of interest. The ranges of values for all parameters across the three sampling months were as follows: colony bee populations 1043–23266, cm^2 brood 8.8–9647, frames of honey 0.5–9.6, and frames of pollen 0.05–3.

Effects of SMR queens, screens and isolation

For average number of varroa mites, the full model analysis detected significant effects for queen type and floor type ($F = 5.5$; df = 1,12; $P = 0.037$). Across the 87-week experiment, the average number of varroa mites retrieved on 24-h sticky sheets was lower in colonies headed by resistant (SMR) queens (7.8 ± 1.1, $n = 317$, mean ± s.e.) than non-selected queens (9.5 ± 1.5, $n = 236$), and mite levels were also lower in colonies with screen floors (6.7 ± 1.0, $n = 275$) than with conventional solid floors (10.4 ± 1.5, $n = 278$). However, because of many interactions we ran analyses by sampling week. On 17 of 22 sampling weeks (spanning 87 weeks), the average number of varroa mites retrieved on 24-h sticky sheets was numerically lower in colonies headed by resistant queens. On four of those weeks, mite numbers were significantly reduced in colonies with resistant queens ($F \geq 7.9$; df = 1,7; $P \leq 0.0264$) (table 2). On 18 of 22 sampling weeks, the average number of varroa mites retrieved on 24-h sticky sheets was numerically lower in colonies with screen floors, but differences were never significant within week. For only one sampling week (October 2003) was a significant effect found for apiary isolation; mite counts were significantly ($F = 48.9$; df = 1,2; $P \leq 0.0198$) higher in isolated apiaries (50.2 ± 37.9, $n = 4$) than non-isolated (0.4 ± 0.3, $n = 3$). Interactions between main effects were detected for weeks 8, 11, 32, and 54 ($F \geq 4.9$; df = 1,7; $P \leq 0.0483$).

Time before reaching treatment threshold (weeks) was significantly affected by type of queen ($F = 933$; df = 1,1; $P = 0.02$). Colonies headed by SMR queens took longer to reach threshold (71.7 ± 3.9 weeks, $n = 14$, mean ± s.e.) than colonies headed by non-selected queens (59.2 ± 4.4, $n = 13$).

Concerning measurements of gross colony condition, the full model ANOVAs detected differences among floor type for

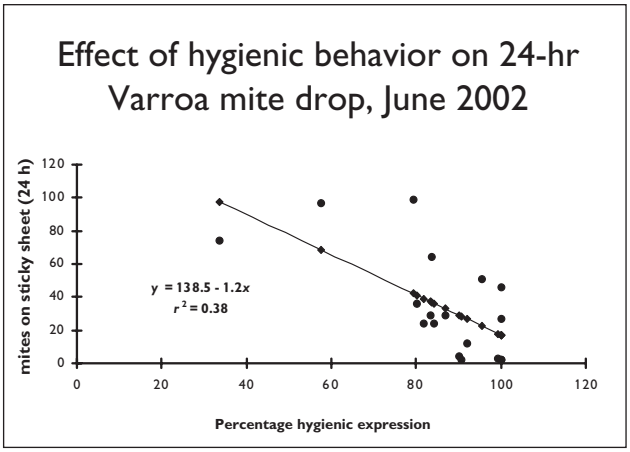

FIG. 1. Linear relationship between number of mites recovered on 24-h sticky sheets and percentage hygienic behaviour expressed by a colony, June 2002.

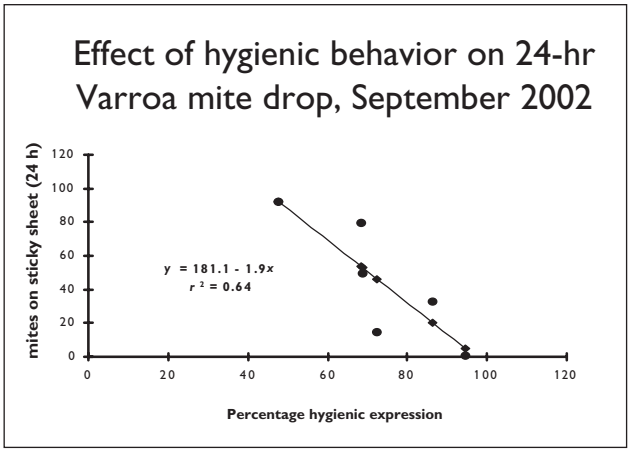

FIG. 2. Linear relationship between number of mites recovered on 24-h sticky sheets and percentage hygienic behavior expressed by a colony, September 2002.

TABLE 2. Average weekly values (± s.e.) for number of mites retrieved on 24-h mite monitoring sticky sheets for colonies headed by non-selected queens and queens selected to express SMR. Numbers in parentheses = *n*. On four sampling weeks in March, April, and May 2003 (*) mite levels were significantly lower in colonies with SMR queens.

Week and date	Non-selected queens	SMR queens
5 (7 May 2002)	0.22 ± 0.1 (20)	0.15 ± 0.1 (20)
8 (28 May 2002)	0.2 ± 0.1 (19)	0.4 ± 0.2 (20)
11 (18 Jun 2002)	0.4 ± 0.1 (19)	0.2 ± 0.1 (20)
14 (9 Jul 2002)	0.5 ± 0.2 (15)	0.1 ± 0.04 (19)
17 (30 Jul 2002)	1.6 ± 0.7 (19)	0.9 ± 0.5 (20)
20 (20 Aug 2002)	3.4 ± 1.5 (19)	0.6 ± 0.2 (19)
23 (10 Sep 2002)	12.6 ± 10.1 (17)	0.4 ± 0.2 (19)
26 (1 Oct 2002)	6.0 ± 1.7 (16)	8.1 ± 3.0 (18)
29 (22 Oct 2002)	3.5 ± 1.0 (15)	5.4 ± 2.5 (19)
32 (12 Nov 2002)	13.5 ± 4.8 (15)	7.4 ± 3.9 (19)
51 (25 Mar 2003)	5.4 ± 1.9 (11)	2.8 ± 0.7 (15)*
54 (15 Apr 2003)	6.5 ± 1.5 (11)	3.3 ± 1.0 (15)*
57 (6 May 2003)	15.7 ± 5.7 (11)	2.3 ± 0.6 (15)*
60 (27 May 2003)	41.2 ± 12.3 (10)	9.8 ± 3.7 (15)*
63 (17 Jun 2003)	41.7 ± 10.9 (7)	25.8 ± 7.9 (13)
66 (8 Jul 2003)	47.7 ± 26.0 (4)	20.4 ± 7.8 (10)
69 (29 Jul 2003)	66.8 ± 35.2 (3)	25.9 ± 11.2 (9)
72 (19 Aug 2003)	11.3 (1)	46.9 ± 18.4 (8)
75 (9 Sep 2003)	1.3 (1)	20.6 ± 10.2 (7)
78 (30 Sep 2003)	34.7 (1)	27.9 ± 26.8 (6)
81 (21 Oct 2003)	47.7 (1)	44.1 ± 16.0 (5)
84 (11 Nov 2003)	73.0 (1)	22.2 ± 13.3 (3)
87 (2 Dec 2003)	NA	9.9 ± 4.7 (3)

frames of honey (F = 6.6; df = 1,12; P = 0.0248) and pollen (F = 4.6; df = 1,12; $P \leq 0.0526$). Across the 87-week experiment, the average number of frames of honey was lower in colonies on screen floors (3.8 ± 0.3, n = 102, mean ± s.e.) than on solid floors (5.1 ± 0.2, n = 117), and likewise frames of pollen was lower in colonies on screen floors (0.9 ± 0.06, n = 118) than on solid floors (1.3 ± 0.06, n = 137). The full model ANOVA detected no effects for queen type on cm^2 brood, but there were significant interactions so analyses were run by week. Of nine sampling weeks, cm^2 brood was significantly higher on two in colonies headed by non-selected queens (table 3).

TABLE 3. Average weekly values (± s.e.) for cm^2 brood for colonies headed by non-selected queens and queens selected to express SMR. Numbers in parentheses = *n*. On two sampling weeks in October 2002 and May 2003 (*) brood production was significantly lower in colonies with SMR queens.

Week and date	Non-selected queens	SMR queens
8 (28 May 2002)	7947 ± 630 (20)	6170 ± 577 (20)
14 (9 Jul 2002)	6213 ± 700 (17)	6103 ± 544 (20)
20 (20 Aug 2002)	4601 ± 203 (17)	4047 ± 354 (20)
26 (1 Oct 2002)	6859 ± 304 (17)	5240 ± 598 (19)*
32 (13 Nov 2002)	741 ± 170 (10)	583 ± 169 (7)
50 (18 Mar 2003)	5370 ± 942 (11)	6183 ± 912 (14)
57 (6 May 2003)	7064 ± 837 (12)	4581 ± 595 (15)*
63 (17 Jun 2003)	8479 ± 907 (11)	8653 ± 609 (15)
69 (30 Jul 2003)	7732 ± 764 (3)	7659 ± 422 (9)

DISCUSSION

The results of the two independent experiments can be summarized as follows: Screen hive floors tend to reduce colony varroa mite levels; on the majority of sampling episodes the number of mites retrieved on sticky sheets was numerically lower, sometimes significantly, in colonies with screen floors (table 1 and text). Likewise, mite-resistant queens tended to cause a numeric and sometimes significant reduction in mite levels; number of mites on sticky sheets decreased as the percentage expression of hygienic behaviour in a colony increased (figs 1 and 2), and on the majority of sampling episodes the number of mites retrieved on sticky sheets was numerically lower in colonies with SMR queens (table 2). Time until achieving treatment threshold is significantly delayed in colonies with SMR queens (*c.* 72 weeks) compared to non-selected queens (59); this benefit was not realized in the first study although time before threshold was delayed numerically in colonies with screen floors (13.4 months) compared to solid floors (11.6). Screen floors may have negative effects on some measures of colony productivity; in the second experiment screens significantly reduced frames of stored honey and pollen. Finally, SMR queens tend to have reduced brood production, sometimes significantly (table 3). Apiary isolation was shown to be virtually insignificant in our study; its direct effects were detectable only one sampling week when mite levels were higher in isolated apiaries. However we deem this a sampling artefact owing to small sample sizes and the observation that mean mite levels were less divergent the sampling weeks before and after.

Our study independently confirms the work of other authors, contributes additional information about hive screen floors, demonstrates interactions between main IPM components, and provides the first evidence that IPM practices delay treatment threshold in varroa mites. To begin, we confirm the efficacy of hygienic and SMR queens at reducing colony varroa mite levels as reported previously (Spivak, 1996; Harbo & Harris, 1999; Harbo & Hoopingarner, 1997; Rinderer *et al*., 1997). We demonstrate a negative linear association between the degree of expression of hygienic behaviour and colony mite levels (figs 1 and 2). We demonstrate a general reduction in brood production in colonies with SMR queens. This effect was also detected by Harbo & Harris (2001) who found reduced brood production in SMR queens inseminated with SMR drones, but in their case this liability was offset when SMR queens were open-mated to non-selected crosses; such compensation was not apparent in our study since a large fraction of our SMR queens were open-mated daughters of instrumentally-inseminated SMR mothers.

Concerning screen hive floors, our study contributes to an evidential base indicating weak effects on bees and mites. In table 4 we attempt to summarize this literature. In most cases the effects of screens are either innocuous or beneficial. The present study is the first to report a significant liability: the finding in the second experiment that screens reduced honey and pollen stores. Nevertheless we believe that the balance of evidence tips in favour of screen hive floors. They exert a modest restraint on mite population growth and a modest stimulus to brood production. Moreover, their cost-benefit profile is considered good, based on an expected useful life of 10 years (Rice *et al*., 2004).

TABLE 4. Summary of some literature (including present study) on average effects of screen hive floors on bees and varroa mites. Non-significant numeric trends are distinguished from statistically significant differences.

Source	Effects on varroa	Effects on bees
Rodionov & Shabarshov (1986)	Mite populations "may be considerably reduced."	
Pettis & Shimanuki (1999)	Numerically reduced sticky sheet mite counts.	Significantly increased brood production.
Ellis *et al.* (2001)[a]	Numerically reduced colony mite populations and sticky sheet mite counts. Numerically reduced percentage mite population in brood.	Numerically increased brood production.
Ellis *et al.* (2003)	Numerically increased number of mites per adult bee.	Numerically increased brood production in 2 apiaries, 1 significantly. Significantly increased bee weight. Significantly increased colony adult bee populations. Did not affect colony weight gain (numerically reduced in 1 of 2 apiaries). Did not affect pollen stores.
Rinderer *et al.* (2003)[a]	Numerically reduced colony mite populations.	Did not affect brood production. Did not affect colony adult bee populations.
Harbo & Harris (2004)	Significantly reduced colony mite populations. Significantly reduced percentage mite population in brood.	Significantly increased cells of capped brood. Numerically increased colony adult bee populations.
Present study	Numerically reduced sticky sheet mite counts on 11 of 16 months, 2 significantly. Numerically reduced sticky sheet mite counts on 18 of 22 sampling weeks. Numerically prolonged months to threshold.	Significantly reduced frames of honey. Significantly reduced frames of pollen.

[a]Comparison limited to 'screen only' treatment vs. control.

Our study joins a relatively small body of papers that tests a multi-component IPM approach against *V. destructor* (Ellis *et al.*, 2001; Rinderer *et al.*, 2003, 2004; Rice *et al.*, 2004; Sammataro *et al.*, 2004). Implicit in this approach are expectations that multiple tactics (1) reduce the likelihood of pests evolving resistance to any one, or (2) interact such that control is enhanced or compensatory control provided if one component fails. With the current study and available literature, assumption (2) is available for scientific consideration.

Of the studies cited above, only the designs of Rinderer *et al.* (2003, 2004) resemble ours in permitting an examination of interacting fixed-effect IPM components. No interactions were detected by Rinderer *et al.* (2003) between bee stock type (Russian or Italian), floor type (screen or solid), and formic acid (applied or not). However, Rinderer *et al.* (2004) found evidence for enhanced mite control in a two-component system employing resistant (Russian) queens and sunny (versus shaded) apiary locations. In the present study, six of eight cases of main effects interaction were favourable in a compensatory manner. In week 54 of the second experiment (15 April 2003) 24-h mite counts were lowest in colonies with SMR queens and screen hive floors; on this particular date screens had failed to reduce average mite numbers, but if the screened colonies also possessed a resistant queen then control was elevated to the highest across the experiment. In the other cases of favourable interaction, mite counts were reduced in colonies in non-isolated apiaries (otherwise with higher average mite levels) if those colonies had screen floors or resistant queens. Although Ellis *et al.* (2001) did not employ a test of interactions, they found evidence for compensatory action by screen floors in colonies with fluvalinate-resistant mites. We believe that the sum of evidence supports the continued use of multi-component tactics against *V. destructor*.

Finally, the present study consummates earlier work on treatment thresholds (Delaplane & Hood, 1997, 1999; Strange & Sheppard, 2001) by demonstrating that IPM practices, most notably mite resistant queens, can be expected to delay onset of treatment threshold and the need to apply chemicals. This objective should underpin varroa IPM projects until fixation of genetic mite resistance in honey bee populations renders acutely toxic acaricides obsolete.

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REFERENCES

BURGETT, M; BURIKAM, I (1985) Number of adult honey bees (Hymenoptera: Apidae) occupying a comb: a standard for estimating colony populations. *Journal of Economic Entomology* 78: 1154–1156.

DELAPLANE, K S; HOOD, W M (1997) Effects of delayed acaricide treatment in honey bee colonies parasitized by *Varroa jacobsoni* and a late-season treatment threshold for the southeastern USA. *Journal of Apicultural Research* 36(3/4): 125–132.

DELAPLANE, K S; HOOD, WM (1999) Economic threshold for *Varroa jacobsoni* Oud in the southeastern USA. *Apidologie* 30: 383–395.

DUNG, N VAN; TAN, N Q; HUAN, L V; BEETSMA, W J (1995) Bio-technical manipulations used in Vietnam to control *Varroa jacobsoni* and *Tropilaelaps clareae* in colonies of *Apis mellifera. Bee Science* 4: 11–13.

ELLIS, J D JR; DELAPLANE, K S; HOOD, W M (2001) Efficacy of a bottom screen device, Apistan, and Apilife VAR in controlling *Varroa destructor*. *American Bee Journal* 141(11): 813–816.

ELLIS, J D JR; DELAPLANE, K S; HEPBURN, R; ELZEN, P J (2003) Efficacy of modified hive entrances and a bottom screen device for controlling *Aethina tumida* (Coleoptera: Nitidulidae) infestations in *Apis mellifera* (Hymenoptera: Apidae) colonies. *Journal of Economic Entomology* 96(6): 1647–1652.

FAKHIMZADEH, K (2000) Potential of super-fine ground, plain white sugar dusting as an ecological tool for the control of varroasis in the honey bee (*Apis mellifera*). *American Bee Journal* 140(6): 487–491.

FELDLAUFER, M F; PETTIS, J S; KOCHANSKY, J P; SHIMANUKI, H (1997) A gel formulation of formic acid for the control of parasitic mites of honey bees. *American Bee Journal* 137: 661–663.

HARBO, J R; HARRIS, J W (1999) Selecting honey bees for resistance to *Varroa jacobsoni*. *Apidologie* 30: 183–196.

HARBO, J R; HARRIS, J W (2001) Resistance to *Varroa destructor* (Mesostigmata: Varroidae) when mite-resistant queen honey bees (Hymenoptera: Apidae) were free-mated with unselected drones. *Journal of Economic Entomology* 94: 1319–1323.

HARBO, J R; HARRIS, J W (2004) Effect of screen floors on populations of honey bees and parasitic mites (*Varroa destructor*). *Journal of Apicultural Research* 43(3): 114–117.

HARBO, J R; HARRIS, J W (2006) Suppressed mite reproduction explained by the behaviour of adult bees. *Journal of Apicultural Research* 45 (in press).

HARBO, J R; HOOPINGARNER, R A (1997) Honey bees (Hymenoptera: Apidae) in the United States that express resistance to *Varroa jacobsoni* (Mesostigmata: Varroidae). *Journal of Economic Entomology* 90(4): 893–898.

HOOPINGARNER, R (2001) Biotechnical control of varroa mites. *In* Webster, T C; Delaplane, K S (eds) *Mites of the honey bee*. Dadant; Hamilton, IL, USA; pp. 197–204.

IBRAHIM, A; SPIVAK, M (2004) The relationship between suppression of mite reproduction (SMR) and hygienic behaviour. *American Bee Journal* 144 (5): 406.

METCALF, R L (1982) Insecticides in pest management. *In* Metcalf, R L; Luckmann, W H (eds) *Introduction to insect pest management*. John Wiley; New York, USA; pp. 217–277 (2nd edition).

PENG, C (1992) Honey bee grooming behavior in Varroa mite resistance. *Bee Science* 2(4): 200–201.

PETTIS, J S; SHIMANUKI, H (1999) A hive modification to reduce varroa populations. *American Bee Journal* 139: 471–473.

RICE, N D; WINSTON, M L; HIGO, H A (2004) Integrated pest management for the parasitic mite *Varroa destructor* (Anderson and Trueman) in colonies of honey bees (*Apis mellifera*). *American Bee Journal* 144(10): 791–795.

RINDERER, T E; KUTSNETZOV, V N; DANKA, R G; DELATTE, G T (1997) An importation of potentially varroa-resistant honey bees from far-eastern Russia. *American Bee Journal* 137(11): 787–789.

RINDERER, T E; DE GUZMAN, L I; DELATTE, G T; HARPER, C (2003) An evaluation of ARS Russian honey bees in combination with other methods for the control of varroa mites. *American Bee Journal* 143(5): 410–413.

RINDERER, T E; DE GUZMAN, L I; HARPER, C (2004) The effects of co-mingled Russian and Italian honey bee stocks and sunny or shaded apiaries on varroa mite infestation level, worker bee population and honey production. *American Bee Journal* 144(6): 481–485.

RODIONOV, V V; SHABARSHOV, I A (1986) *The fascinating world of bees*. Mir Publishers; Moscow, Russia.

SAKOFSKI, F; KOENIGER, N; FUCHS, S (1990) Seasonality of honey bee colony invasion by *Varroa jacobsoni* Oud *Apidologie* 21(6): 547–550.

SAMMATARO, D; DEGRANDI-HOFFMAN, G; WARDELL, G; FINLEY, J; OSTIGUY, N (2004) Testing a combination of control tactics to manage *Varroa destructor* (Acari: Varroidae) population levels in honey bee (Hymenoptera: Apidae) colonies. *International Journal of Acarology* 30(1): 71–76.

SAS INSTITUTE (1992) *SAS/STAT user's guide, version 6*. SAS Institute; Cary, NC, USA; 846 pp. (4th edition).

SCHULZ, A; KOENIGER, N; RUTTNER, F (1983) Drohnenbrut als Varroa-Falle. *Imkerfreund* 38: 50–51.

SKINNER, J A; PARKMAN, J P; STUDER, M D (2001) Evaluation of honey bee miticides, including temporal and thermal effects on formic acid gel vapours, in the central south-eastern USA. *Journal of Apicultural Research* 40(3–4): 81–89.

SPIVAK, M (1996) Honey bee hygienic behavior and defense against *Varroa jacobsoni*. *Apidologie* 27: 245–260.

SPIVAK, M; REUTER, G S (1998) Honey bee hygienic behavior. *American Bee Journal* 138(4): 283–286.

STRANGE, J P; SHEPPARD, W S (2001) Treatment thresholds and timing for the control of *Varroa destructor* in honey bee colonies in Washington State. *Journal of Economic Entomology* 94: 1324–1333.

WILKINSON, D; THOMPSON, H M; SMITH, G C (2001) Modeling biological approaches to controlling Varroa populations. *American Bee Journal* 141(7): 511–516.