World Honey Bee Health: The Global Distribution of Western Honey Bee (*Apis mellifera* L.) Pests and Pathogens

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Introduction

Western honey bees, *Apis mellifera* L., (hereafter "honey bee") are among the most widespread organisms in the world, as their association with humans has led to their dispersal from their native range in Europe, the Middle East, and Africa to every continent except Antarctica (Crane, 2013). They are economically important because of their role as pollinators of numerous agricultural crops, honey producers, and producers of various hive-related commodities (*e.g.* beeswax, propolis, royal jelly) (Southwick & Southwick, 1992). Given their economic importance, honey bees are the subject of intense scientific investigation, much of which focuses on honey bee health and productivity.

Honey bees host a suite of pests and pathogens, many of which are capable of killing colonies outright (Cornman et al., 2012). Correspondingly, beekeepers around the world spend considerable time managing for these biotic colony stressors while scientists work to develop comprehensive research programs focused on the biology, pathology, and control of these organisms. Knowing the global distribution of the honey bee pests and pathogens is key to developing strategies for their control and limiting their further spread.

Bradbear (1988) and Matheson (1993, 1995, 1996) were first to publish reviews of the global distributions of honey bee pests and pathogens. Their work was followed by Allen and Ball (1996) who developed a similar review, but for the major honey bee viruses. Subsequently, Ellis and Munn (2005) combined these reviews into a single treatise and included updated information on new pests/pathogens and the expanding distribution of established ones.

The intent of our review is to update the work of Ellis and Munn (2005), with a special emphasis on new and emerging pests/pathogens, as well as noting the spread of those discussed in the earlier reviews. The last 15 years (2005–2020) were marked by an extraordinary interest in honey bees, sparked by the international emphasis on elevated loss rates of managed honey bee colonies reported in parts of the world (Antúnez et al., 2017; Brodschneider et al., 2018; Currie et al., 2010; Dahle, 2010; Ellis et al., 2010; Kulhanek et al., 2017; Pirk et al., 2014). The effort to identify the main drivers associated with elevated colony losses led to a surge in refereed publications on honey bee pests and pathogens, both newly discovered and previously known (Steinhauer et al., 2018). This global emphasis on colony losses motivated our desire to publish an updated review of the worldwide distribution of honey bee pests and pathogens.

Unlike in the previous reviews, we elected to post pest/pathogen distribution tables and maps on a new website: www.worldhoneybeehealth.com. The direct links to the appropriate distribution tables and maps (example map: Figure 1) for each pest and pathogen are included in the table published on the website. This strategy is useful for two primary reasons. First, posting the maps and tables online allows us to change entries in real time without having to publish a new manuscript to announce these changes. This, then, permits us to fix distribution errors such as accidental omissions from certain locations (i.e. failing to note that a pest/pathogen is in a given country) or, perhaps more importantly, accidental inclusions for certain locations (i.e. saying a pest/pathogen is in a country when it is not). The latter is particularly important given that government or other authorities in some countries may initiate regulatory actions based on the distributions highlighted in our review. It also allows us to add new or emerging pests/pathogens as they are discovered. Thus, having the distribution maps and tables online allows us to fix, in real time, any errors pointed out to us and *substantiated with data*.

Second, posting the maps and tables online allows us to make high resolution copies of them downloadable and useful for inclusion in presentations, manuscripts (refereed and popular), reports, websites, etc. *We encourage and endorse the use of the tables and maps for these purposes.* Our only request is that the tables, maps, and this manuscript be cited appropriately *at each use*, regardless of the way used.

What follows is a discussion of our strategy for developing this review. We

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outline the methods and criteria we used when deciding how to categorize pest and pathogen presence/absence/etc. in a country. We also detail the process for reporting errors to us and provide citation instructions to follow when using the tables and/or maps for any purpose. We conclude with a discussion of our plans for modifying and expanding the functionality of the website (www.worldhoneybeehealth.com). We hope that the website and the information contained therein will be a valuable tool to scientists, regulators, industry officials, beekeepers and more as we all work together to try to improve the health of this valuable bee species.

Methods

Determining a Country's Pest/Pathogen Status

We implemented several strategies to ensure the data presented in the tables and maps are valid and accurate. First, we followed the precedent set by previous reviews (Allen & Ball, 1996; Bradbear, 1988; Ellis & Munn, 2005; Matheson, 1993, 1995, 1996) when determining the disease/pest status in a given country. We did not cite unpublished results or anecdotal reports. Instead, the following scientific databases were used to find authoritative sources of information for pest/pathogen distribution: Web of Science, PUBMED, and Google Scholar. The name of the pest or pathogen and the name of the country were used as the search terms in these databases and the results from all years are included in the maps and tables at www.worldhoneybeehealth.com. Members of our team will update the maps and tables early every year to reflect new information reported for any pest/pathogen the previous year. For example, the 2020 literature will be searched in early 2021 to update the maps and tables accurately through 2020. Otherwise, maps and tables will be updated throughout the year only if new findings are brought to our attention via the appropriate reporting avenue (see: **Updates and Use of Information** below).

We were only able to include information from sources or summaries of sources written in English. We recognize this limitation and encourage users of the website to notify us of any missing information regarding the distribution of honey bee pests/pathogens. If aware of a non-English source we need to include, please provide the source and a translation to us for evaluation following the instructions on the website.

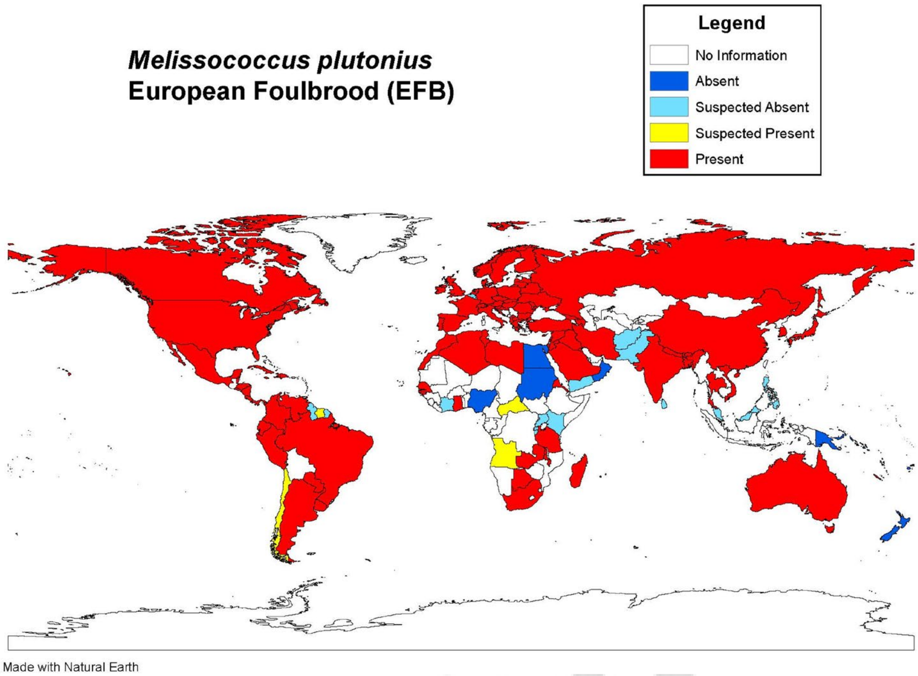

Figure 1. Global distribution of *Melissococcus plutonius* (European foulbrood) in 2020. Visit www.worldhoneybeehealth.com for the most up-to-date version of this map.

Table 1. Criteria for determining the country status of a given honey bee pest or pathogen.

Criteria	Country color	Symbol used in the tables	Criteria employed
Confirmed Present	Red	(+)	Reported present in a peer-reviewed article or an authoritative review or investigation; report by apparently reliable witness of a pest/pathogen recognizable by visible signs of infestation/infection in the field and/or using standard laboratory techniques.*
Suspected present	Yellow	(+)?	Anecdotal or hearsay report; field diagnosis of condition with or without obvious signs of infestation/infection in the field. Presence not confirmed using standard laboratory techniques.
Suspected absent	Light Blue	(-)?	Limited investigation made with negative results; anecdotal reports about absence of pest/pathogen and absence of signs of infestation/infection in the field.**
Absent	Blue	(-)	Rigorous survey performed, with confirmed absence of the specific pest/pathogen using field and laboratory analyses.
No information	White		No information available; may be anecdotal reports on the absence of signs of infestation/infection.

*The pest/pathogen identity should be confirmed using standard laboratory practices or techniques generally accepted for the given pest or pathogen (Dietemann et al., 2013). Admittedly, a pest/pathogen can be eradicated from a country, meaning that a previous "confirmed present" may now be "suspected absent" or "absent".

**This assignment does not preclude the presence of a given pest or pathogen in the country. A pest or pathogen can be present in a country for some time before it is discovered.

We used the criteria, outlined by Ellis and Munn (2005) and in Table 1, to confirm the pest/pathogen status for each country.

Geopolitical Issues

This review is intended to describe the worldwide occurrence of western honey bee pests and pathogens *at the country level*. It is not intended to illustrate regional, provincial, or state occurrence within countries. As an example, an entire country will be highlighted red even if the pest or pathogen in question is localized to a small area within the country. The available literature is not sufficient to address within-country resolution. As such, conclusions about the distributions within a country should be made with caution and are at the discretion of the reader.

Furthermore, many countries oversee multiple associated territories or states that are separated from their motherland by landmasses, bodies of water, etc. Examples include Australia, France, Italy, Netherlands, Spain, United Kingdom, the United States, etc., all of which have territories, states, etc. that are not contiguous with the land recognized as the principal landmass that composes the country. In these cases, the associated states/territories/etc. were treated independently from their motherland. For example, Puerto Rico is a U.S. territory located in the Caribbean Sea. The presence of a pest on the U.S. mainland would not result in Puerto Rico being colored to reflect that status, unless Puerto Rico also hosts the pest, and *vice versa*.

As for the previous reviews, it is somewhat difficult to address pest and pathogen presence from reports originating from now-defunct political entities. For example, reports from decades ago would have been made for the former Czechoslovakia, Yugoslavia, etc. These and other political entities no longer exist, being split into multiple countries or being absorbed into existing ones. We tried to report pest and pathogen presence from the new geopolitical entities where possible. When not possible, all new entities that incorporated part(s) of the old entities were highlighted. We intend to fix this problem (i.e. geopolitical changes over time) in the future by incorporating GPS coordinates for the locations the various pathogens/pests were found.

Furthermore, not all countries have robust beekeeping and/or scientific communities.

This, then, hinders knowledge about the occurrence of certain pests and pathogens in their borders. We hope that this manuscript is a call-to-arms for those countries, encouraging the reporting of pest and pathogen occurrence to the international community. Finally, we used the English names for all countries/states/territories.

Pests and Pathogens Included in This Review

We included the selected pests/pathogens in this review based on the organism's capacity to cause damage to an individual honey bee or a honey bee colony. Some inclusions were obvious (e.g. the small hive beetle - *Aethina tumida*, and the mite *Varroa destructor* – Figure 2).

Others, such as various microbes (including viruses), were not as obvious.

Regarding microbes, a standard approach to identifying an organism as disease causing is the demonstration of Koch's postulate (Evans, 1995). Several honey bee pathogens are relatively easy to isolate, purify and reintroduce into the bee to produce the same signs of disease, thus demonstrating the postulate.

Viruses, on the other hand, are more problematic. Honey bee virologists lack a reliable way to isolate viruses, making the fulfilment of Koch's postulate a significant challenge in some instances. Molecular techniques allow us to identify virus replication with some level of precision (Boncristiani et al., 2009). However, replication *per se* does not tell us if that specific virus is harming the bee or the colony. Therefore, we decided to include in this review all viruses detected in honey bees and discussed as pathogenic.

Another challenge we continue to encounter regarding pathogen/pest inclusion is the ever-evolving knowledge about certain organisms that makes country-level resolution about their distribution difficult to confirm. For example, Ellis and Munn (2005) discuss *Nosema apis* as the exclusive *Nosema* species in their review. At the time, it was the only known *Nosema* species infecting honey bees. Since that review, *N. cerana* (Higes et al., 2006) and, more recently, *N. neumanni* (Chemurot et al., 2017) have been discovered. This, of course, raises suspicions that the literature might be fraught with misidentified *Nosema*, calling into question distributions assumed from the older literature. We list a few other examples of this below to highlight some of the problems

Figure 2. Example of honey bee maladies. A - *Apis mellifera* infested with *Varroa destructor* and showing signs of *Deformed wing virus* (DWV) infection; B - *Aethina tumida* (small hive beetle) adult.

associated with developing distribution maps (the list is not inclusive):

- *Varroa destructor* as an example of a misidentified species – Until 2000, this mite was identified as *Varroa jacobsoni*, which we now know is a separate species (Anderson & Trueman, 2000). Correspondingly, the distribution data on this mite prior to 2000 is suspect.
- Wax moths as an example of lack-of-resolution – Many authors in the older literature fail to name which species of wax moth is being studied in a given manuscript. Thus, we only know the distribution at the level of "wax moth" rather than at the level of species: i.e. greater (*Galleria mellonella*) or lesser (*Achroia grisella*) wax moth.
- *Tropilaelaps* spp. as an example of limited knowledge on an organism – There are multiple species of *Tropilaelaps*. The one of chief concern is *T. clareae*. We know little about its natural distribution.
- Viruses as an example of strain/variant identity – Name confusion in the literature can even occur with viruses. For example, *Deformed wing virus* is now recognized as at least four distinct variants (DWV-A, -B, -C, and -D). The older literature recognizes only DWV while much of the new literature provides strain-level resolution.

In cases like these, we created distribution maps and tables at the lowest level of resolution possible. For example, we created a *Nosema* spp. map which includes distribution information on "*Nosema*" when only *N. apis* was known, recognizing that the old reports of *N. apis* may include misidentifications of *N. ceranae* and *N. neumanni*. Then, we created maps for all three species where the species identity was confirmed according to our strict criteria (outlined in **Determining a country's pest/pathogen status** and Table 1). The result is a distribution map where the species resolution is not trustworthy ("*Nosema* spp.") and maps where it is trustworthy (*N. ceranae*, *N. apis*, and *N. neumanni*), but likely underrepresented. The same is true for all pests/pathogens where similar situations occur. We intend to develop distribution maps and tables for each species as reliable distribution data become available.

Additional Comments

While Ellis and Munn (2005) included some information about other species of honey bees in their review, we limited our review to pests and pathogens associated with *A. mellifera* specifically. This allowed us to narrow our scope and attempt to provide detailed coverage for this honey bee.

Where possible, we cited the previous world honey bee health reviews (Allen & Ball, 1996; Bradbear, 1988; Ellis & Munn, 2005; Matheson, 1993, 1995, 1996) rather than the original sources to streamline our citations. Readers are encouraged to revisit the earlier reviews if interested in obtaining the original sources on the country-level distribution of a particular pest or pathogen. We plan to include links to original citations in the online tables as this project grows.

We acknowledge that a new report of a pest or pathogen in a country does not necessarily represent its "spread" to that country since the last review (Ellis & Munn, 2005). It is possible that the pest/pathogen was present in the country earlier and that its occurrence failed to make it to the refereed literature or that it was altogether unnoticed.

The constant improvement of high throughput molecular techniques for pest and pathogen detection allows researchers to investigate the different environments in which honey bees can live, thus leading to additional discoveries related to their pests and pathogens. A significant amount of data on honey bee pests and pathogens are being generated every year and many new organism are being discovered. We realize that the discovery of new organisms associated with honey bees does not imply a biological relationship between the two. Therefore, a newly discovered organism needs to be confirmed as a true pest or pathogen (i.e. causes some harm to the individual bee or colony) before we will include it in our growing database.

Correspondingly, we will modify our tables and figures (i.e. add or retract information) as new information becomes available.

Updates and Use of Information

We adopted an interactive system whereby the maps and tables provided at www.worldhoneybeehealth.com can be updated as needed by the author team as new information becomes available. This strategy will allow for updates to the global honey bee health status as new pests/pathogens, updated nomenclature, and other changes emerge. This also allows readers/users to provide updates to us directly, updates that can include new occurrences of a pest/pathogen in a country, errors (inclusion or omission errors) in the online tables/maps, etc. The procedure for reporting updates/errors follows:

- Email WHBH@ifas.ufl.edu

Please include the following information:

- Your name, affiliation, and contact information (email address required)
- The proposed change (omission error, inclusion error, or new country status of a disease or pest)
- Attach a peer-reviewed manuscript or other documentation to support the change.
- Include any other information you feel is relevant.

The submitted information will be reviewed by the author team and an amendment made to the tables and/or maps as deemed appropriate.

All tables and maps are free to download and use (they are open source). High resolution images were used to generate each map. Consequently, you can see country status by zooming into the region or country of interest if the land area is too small to see at the whole map level.

All tables, maps, and this manuscript must be cited appropriately *at each use*. The appropriate citation to include for maps, tables, and this manuscript is:

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Conclusion

Upon finalizing our review, we developed three recommendations we wish to make to individuals interested in or actively conducting research on honey bee pests and pathogens.

1. *Always* use diagnostic tests to confirm the exact species or strain of the test organism. This will help remove ambiguities surrounding pest/pathogen identification. Molecular diagnostics, where available, are preferable. The definitive guide for this, to date, is the COLOSS *BEEBOOK* Volume II: Standard Methods for *Apis mellifera* Pest and Pathogen Research (Dietemann et al., 2013). This guide will undergo future updates to ensure that the methods for pest/pathogen identification it includes are up-to-date.
2. *Always* include GPS data for the location of each pest/pathogen you find/report and each study you conduct on a pest/pathogen. With the widespread availability of GPS devices, it is common for people to publish the GPS location of a pest/pathogen at first discovery, identification, or occurrence in a location. This is fitting and appropriate. However, many scientists do not publish GPS information about their research projects when studying a particular pest or pathogen. If such information were included in all refereed manuscripts in which studies on pests/pathogens are reported, we would be able to improve the pest/pathogen distribution resolution beyond country in our maps.
3. Where possible, maintain the archived sample that was used to create the record for the pest or pathogen in a given location. The sample should be curated properly and protected for future research uses.

In conclusion, we hope this review will serve as a resource on honey bee health to honey bee scientists, beekeepers, industry, the general public and various government agencies. We believe that information on honey bee pest and pathogen distributions will allow the honey bee community to make science-based decisions that will improve honey bee health and the sustainability of beekeeping globally.

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