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Review article

Coordinated responses to honey bee decline in the USA*

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Abstract – In response to successive years of high honey bee mortality, the United States Congress mandated the US Department of Agriculture (USDA) to increase funding for research and education directed at reducing honey bee decline. The funding follows two administrative streams within USDA – one through the USDA Agricultural Research Service (ARS) and another through the USDA National Institute for Food and Agriculture (NIFA). ARS is funding an Areawide Project operated by the four ARS honey bee labs, and NIFA is funding through a competitive grant process a Coordinated Agricultural Project (CAP) operated by scientists and educators heavily represented by state colleges of agriculture. Each project – Areawide and CAP – is characterized as a consortium of investigators working in a coordinated manner to reduce institutional redundancy and optimize the discovery and delivery of sustainable bee management practices to client beekeepers.

***Apis mellifera* / pollinator decline / colony collapse disorder / CCD / research / education / honey bees / *Nosema* / integrated pest management / nutrition**

1. INTRODUCTION

Honey bee decline in the United States is nothing new. Data collected by the US Department of Agriculture (USDA) show a pattern of steady decline in the numbers of managed hives from a peak of nearly 6 million in the 1940s to 2.3 million by 2008 (Fig. 1). The suspected causes for this are many and include trans-global pathogens and parasites (Ellis and Munn, 2005) as well as socioeconomic trends that serve to push beekeepers out of practice, as seems to be the case throughout virtually all of Europe (Potts et al., 2010). This downward spiral in the United States went from bad to worse in the opening decade of this century. In the winter of 2004–2005, beekeepers began reporting unusual colony losses in California where colonies were collapsing in advance of almond pollination in February and March of 2005. A survey of strong and weak colonies in seven commercial operations representing six states failed to point to any one cause when evaluations by the USDA Beltsville Laboratory were limited to parasitic mites, *Nosema* and viruses (Anonymous, 2005). In the fall of 2005, following continued reports of colony and queen problems, a meeting of approximately 40 industry leaders and researchers was held in Lincoln, Nebraska to discuss colony declines. No definitive conclusions were reached, but all in attendance agreed that colony losses and queen problems were greater in scope than in previous years; this seemed to hold true even for beekeeping operations that had changed little over the past 20 years, even with the acknowledged impact of *Varroa*. The group also considered the role of pesticides, both in-hive (Pettis et al., 2004) and agricultural (Nguyen et al., 2009). Following this meeting, the USDA initiated a nutrition and bee stock study in Bakersfield, California and found that supplemental

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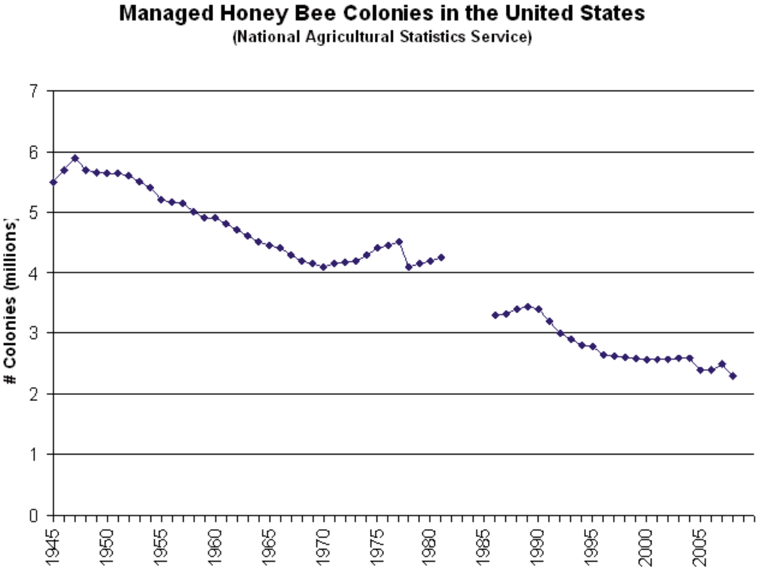

Figure 1. The number of managed honey bee colonies (in millions) in the United States from 1945 to 2008 as reported by the USDA National Agricultural Statistics Service. The current level of approximately 2.5 million colonies is very low given that the US needs 1.5 million colonies in California each year to pollinate almonds. Three years of on average 30% colony losses in the US (2006–2008) threaten our ability to provide such pollination services to agriculture. No data on colony numbers were recorded for 1982–1985.

feeding stabilized colony strength but did little to increase colony size for almond pollination (DeGrandi-Hoffman et al., 2008). This reduction in managed colonies, coupled with increased colony mortality, has resulted in increased pollination fees for almonds and other crops; for example, in almonds the fee per colony has risen from $75 to $150 and in blueberries a similar doubling of pollination fees has occurred. The almond industry alone needs 1.5 million colonies annually for pollination, more than half the nation's colony reserves. Even though beekeepers can partially recover winter losses with spring-time splits (managed colony division), this practice cannot compensate for successive winter losses hovering near 30% (vanEngelsdorp et al., 2008, 2010). In this sense the situation in the US is more grave than that reported by Aizen and Harder (2009) for the global scale. Those authors showed that the global area of pollinator-dependent crops is increasing faster than the growth in global reserves of bee hives. In the US the increase in pollinator-dependent crops is accompanied by a decrease in the national reserve of bee hives. More than anything else, this fact constitutes the nexus of the perceived pollinator deficit in US agriculture.

Among the dead colonies piling up during these years was a group expressing a delimiting set of symptoms – a condition which has come to be called Colony Collapse Disorder or CCD. The symptoms assigned to CCD include (1) the dwindling or near complete loss of adult bees with few or no dead bees around the hive, (2) low ratio of adult bees to remaining brood, (3) a disproportionately young workforce, (4) reluctance of dwindling colonies to consume food provided by the beekeeper, and (5) reluctance of neighboring bees to rob the colony once it is dead (Ellis et al., 2010; vanEngelsdorp et al., 2010). Colonies categorized with CCD were subsequently shown positive for multiple pathogens, including virus and *Nosema* spp., and there is evidence that the causative agents are communicable (Cox-Foster et al., 2007; vanEngelsdorp et al., 2009). The term CCD has met with resistance by some American scientists who view it as too symptom based which takes away from objective attempts to assign etiology and causation to bee disorders. At the very least it is important to desynonymize CCD from bee decline in general. Bees die from many things, and CCD is just one of them (Neumann and Carreck, 2010; Genersch et al., 2010, this issue). From a scientific perspective, CCD is best thought of as a syndrome – a set of symptoms inviting scrutiny by experimenters armed with Koch's Postulates and intent on parceling out the constituent or interacting agents. In beekeeper surveys, the fraction of U.S. colony winter deaths attributed to CCD has ranged from 36–60% (vanEngelsdorp et al., 2010).

In October 2006, the National Research Council released its seminal report, Status of Pollinators in North America (NRC, 2007), awakening a general awareness of the decline of honey bees and other pollinators. The NRC report was followed by three papers documenting successive colony mortality in the United States for the winters of 2006–2009 at 32%, 36% and 29% (vanEngelsdorp et al., 2007, 2008, 2010) and yet more papers reinforcing that colony numbers are necessarily important to global agriculture (Klein et al., 2007) and at the same time failing to keep pace with a growing demand for pollinator-dependent crops (Aizen and Harder, 2009). The reaction by beekeepers and the public has been immediate and sustained. Meetings and Congressional hearings were held in 2007 and 2008 and a CCD Action Plan was drafted to serve as a guide to a coordinated national research and education response aimed at reversing honey bee decline.

The agency charged to administer these Congressional mandates is the cabinet-level US Department of Agriculture (USDA), and within USDA the two divisions most directly involved with bee research are the Agricultural Research Service (ARS) and the National Institute for Food and Agriculture (NIFA), formerly known as the Cooperative State Research, Education, and Extension Service (CSREES). Each of these divisions represents a funding stream for one of the two coordinated projects described in this paper.

ARS is the administrative home of the five federal bee labs, including the Bee Research Laboratory in Beltsville, Maryland, specializing in honey bee diseases and pests; the Honey Bee Breeding, Genetics, and Physiology Laboratory in Baton Rouge, Louisiana, dedicated to improving honey bee stock and honey bee management; the Honey Bee Research Unit at Weslaco, Texas, emphasizing studies on Africanized honey bees and management of honey bee parasites and stresses; the Carl Hayden Bee Research Center in Tucson, Arizona, concentrating on bee nutrition, pollination, and management of Africanized bees and *Varroa* mites; and the Bee Biology and Systematics Laboratory in Logan, Utah, the unit dedicated to the biology, systematics, and management, of non-*Apis* bees.

NIFA is the main conduit for competitive federal grant dollars flowing from Washington to non-federal research and education institutions across the US, most of which are colleges of agriculture in state universities. The beginnings of this system can be traced to the Morrill Act, signed into law by President Abraham Lincoln in 1862, creating the so-called Land Grant system which incentivized states to establish "colleges for the benefit of agriculture and mechanic arts" (NIFA, 2009a). A second Morrill Act of 1890 provided incentives for states to establish colleges of "agriculture and mechanic arts" for historically disadvantaged populations (NIFA, 2009b). Combined, the Morrill Acts have been recognized as synergists for the increase of equal-opportunity education in the United States, drivers for the extension of research-based knowledge into America's rural communities, and partial explanations for America's rise as a technological society in the 20th century. Today, a significant portion of the bee research in the United States, and virtually all of the institutional beekeeping education in the United States, come from universities in the Land Grant system.

USDA has a long history of funding bee research through both administrative streams, ARS and NIFA, but what has changed in recent years is a heightened attention to funding projects of a national scale through a highly managed and coordinated approach that reduces redundancy, maximizes collaborations, and puts a premium on deliverable results. Not one, but two coordinated schemes have emerged from the Congressional mandate – the Areawide Project administered by ARS and the Coordinated Agricultural Project (CAP) administered by NIFA. Each of us is the national director for his respective program – JSP for Areawide and KSD for CAP – and here we give an overview of our programs, their objectives, points of shared collaborations, and expected outcomes. It is not our intent in this paper to review the published experimental material related to colony losses nor the history of losses in the US the but rather to concentrate on more recent colony losses and the coordinated research effort that has developed in the US.

2. USDA-ARS AREAWIDE PROJECT TO IMPROVE HONEY BEE HEALTH

This program will conduct a comprehensive set of demonstration trials across the country bringing together recent ARS research findings on mite-resistant bee stocks, improved diets, mite and disease control alternatives, and general colony management techniques. Each of the four ARS honey bee labs will be responsible for a distinct area of research, but in the case of parasite and pest control and migratory stress reduction some overlap is needed to take advantage of the expertise present in each laboratory. Economic analyses of the various management techniques will be carried out and the findings communicated to stakeholders over the life of the program. The program will involve the interplay between four broad components that impact colony health: (1) bee stock, (2) nutrition, (3) pests and disease control and (4) colony management techniques.

The overarching goal of the Areawide program is to increase colony survival and availability for pollination and thus increase the profitability of beekeeping in the US. To this end, it has enumerated the following objectives:

1. To increase colony strength for pollination of almonds and subsequent crops.
2. To demonstrate that resistant bee stocks reduce operating costs and increase survivorship.
3. To demonstrate improved parasitic mite control with proper timing of application.
4. To improve the content and delivery methods for carbohydrate and protein diets.
5. To improve the integrated use of controls for pests and diseases including nonchemical beekeeping methodology.

The Baton Rouge lab will focus on bee stock improvement and evaluations and improving early spring buildup using genetic selection and colony size. Special attention will be focused on two ARS bee stock improvements – Russian bees and the *Varroa* Sensitive Hygiene (VSH) trait (Baton Rouge) (Rinderer et al., 2010). The Beltsville lab will focus on improving queen longevity, improving *Nosema* controls, investigating the antibiotic Tylosin®, improving non-chemical *Varroa* limiters such as plastic drone comb and screen bottom boards, and identifying and mitigating stressors associated with migratory beekeeping. The Tucson lab will concentrate on nutrient supplements including carbohydrates and the protein supplement Mega Bee® as well as the miticidal properties of 2-heptanone. The Weslaco lab will be working on improved management techniques for *Varroa* including the miticide Hivastan®, along with new controls for *Nosema*, stock improvements with Africanized bees, and mitigating stress associated with migratory beekeeping.

One of the projects tying this together is a test of a year-round management scheme for large migratory and smaller non-migratory beekeeping operations with an emphasis on the larger migratory operations that pollinate California almonds (almost half of all managed bees in the US). Operations are being replicated in each of three geographic regions of the country: East, Mid-West and West. It is imperative to replicate studies across geographic regions because colony growth and disease epidemiology vary markedly in different parts of the country. Mirroring this effort is a sister project of the CAP program which is monitoring a series of stationary apiaries across the country for a variety of health and strength parameters. Collectively, these twin projects will give an unprecedented description of the state of American honey bees with insight into the comparative impacts of stationary versus migratory practices.

In all these efforts we will involve university partners in economic analysis and extension. Technology and knowledge transfer from the Areawide Program will be a group effort with assistance from the American Association of Professional Apiculturists (AAPA) and university personnel, most particularly the CAP program who will conduct beekeeping workshops and field days as part of their mandate for knowledge delivery. The most conspicuous partnership, already launched, is the Bee Health Community of Practice website http://www.extension.org/bee_health, a shared collaboration between the Areawide Program and all entities named above. One of the most important products on this site will be a Best Management Practices literature, regularly updated, and representing the latest science-based recommendations for bee management.

There continue to be emerging issues in the management of honey bees that may require additional research and extension efforts over the life of this project. One example is the recognition of a second species of the internal parasitic microsporidian *Nosema* spp. Another is the CCD phenomenon for which researchers have implicated candidate pathogens (Cox-Foster et al., 2007; vanEngelsdorp et al., 2009) and mechanistic pathways (Johnson et al., 2009). Issues such as these, and new ones, can be expected over the life of the five-year Areawide project and our management scheme must remain flexible to accommodate emerging priorities.

3. NIFA COORDINATED AGRICULTURAL PROJECT

The CAP concept, an innovation of the National Institute for Food and Agriculture (NIFA), is applied broadly to agricultural problems of a national scale. NIFA solicits and awards no more than one CAP project per year. CAP projects are multi-state, multi-institutional, multi-year, national in scope, and integrate research with information delivery to client publics. The idea is to eliminate redundancy and create a seamless transition between new research and the stakeholders who can use it. Examples of other CAP projects include Avian Influenza, Porcine Reproductive and Respiratory Syndrome, and Johne's Disease in cattle. 2008 was the year for Managed Pollinators, and funding was made available at the level of $4.1 million for 4 years. A consortium of over 20 research and extension specialists emerged from a competitive proposal process, representing 18 institutions, including fifteen 1862 Land Grant institutions, one 1890 institution, and two ARS bee labs.

Our approach has been to assume that bee decline is a product of numerous interacting factors, synthetic and organic. Late research seems to bear this out. Colonies expressing symptoms associated with CCD – rapid loss of adult bees and low ratios of adult bees to brood – have been shown to express high rates of mixed infections, including viruses and *Nosema* species (vanEngelsdorp et al., 2009). If viruses are shown to disrupt fundamental processes such as RNA transcription (Johnson et al., 2009) and immune response, this could explain the kind of wide-scale generic bee morbidities described in recent years. At the field level, beekeepers report many suspected causes of winter mortality, the latest data coming from a survey of 2008–2009 winter losses in which beekeepers ranked the following as the top nine contributing factors: starvation, queens, weather, mites, weak in fall, *Nosema*, management, CCD, and pesticides (vanEngelsdorp et al., 2010). And finally, the ubiquity and variety of pesticide residues inside bee hives (Frazier et al., 2008) further strengthen the view that a broad exploratory approach is justified at this early stage of our researches.

Working from this starting point, our consortium has organized itself around four broad objectives:

1. Determine and mitigate causes of bee decline: study the interactive effects of disease agents (pathogens, parasites) and environmental factors (pesticides, nutrition) on honey bee health.

2. Incorporate traits that help honey bees resist pathogens and parasitic mites and increase genetic diversity of commercially available stocks.
3. Improve conservation and management of non-*Apis* pollinators by identifying new or emerging pathogens and parasites, abiotic stresses, habitat degradation, and practices that optimize their pollinating efficacy.
4. Deliver research knowledge to client groups by developing a technology transfer program for queen breeders and a literature on Best Management and Conservation.

Details of the working objectives under each of these goals, including specific collaborators, rationale, and expected outcomes, are viewable at our dedicated website http://www.beeccdcap.uga.edu/. But for our purposes here we give a general overview below.

For goal 1 we are engaged in experiments designed to characterize bee morbidity associated with *Nosema apis* and *N. ceranae*; to characterize epidemiology of Israeli acute paralysis virus and deformed wing virus; to monitor with a standardized sampling scheme the pathogen and pesticide loads in each of seven stationary apiaries in the states of California, Washington, Texas, Minnesota, Florida, Pennsylvania, and Maine; to design diagnostic tools for high-throughput detection of diseases; and to improve basic toxicology on in-hive acaricides and some of the newer generation agricultural pesticides.

The seven-state stationary apiary monitoring scheme described above is one of the points of collaboration between the two coordinated projects described in this paper. Data from the stationary apiaries will be joined with data from colonies managed in a migratory fashion typical for much of the commercial beekeepers in the US and monitored by ARS Areawide. It is hoped that this design will not only give a representative picture of the state of honey bees in the US, but also elucidate the comparative effects of management on honey bee health.

Goal two is designed under the assumption that bee breeding and the conservation of genetic diversity in *Apis mellifera* in the United States are good investments in bee health management that is sustainable and independent of alien chemicals in the bee nest environment. To that end, we have designed research programs to identify genes that confer honey bee resistance to *Varroa destructor* and other biotic stressors. A second working objective is aimed at identifying geographically discrete pockets of honey bee genetic diversity.

The third goal represents our investment in non-*Apis* pollinators. Here we have designed experiments that mirror the pathology and toxicology work in goal one with *A. mellifera*. The mirroring is especially conspicuous in the case of the stationary apiary monitoring scheme in which the collaborators will be doing systematic sampling on-site for non-*Apis* bees and subjecting these samples to disease and pesticide analysis to check for cross-over disorders between bee taxa.

The fourth and final goal represents our investment in one of the pillars of the CAP concept – client delivery. Here we have taken steps to inaugurate face-to-face training sessions for commercial queen breeders in California – the industry sector representing the largest source of queens sold annually in the US – in the methods of genetic selection for disease and mite resistance. Preliminary efforts on the ground have been met with enthusiastic support by the client group. In another example of collaboration between ARS Areawide and CAP, the two groups have partnered to create a "Bee Health" web site at eXtension.org – viewable at http://www.extension.org/bee_health. The eXtension.org network is a nationwide initiative designed to address the problem of information quality on the internet. Its purview is all matters of agricultural extension. The process begins with a candidate "Community of Practice" (CoP), a self-identified group of content specialists who apply to eXtension.org to create and manage an information site on the network. An information site has two "sides", a limited-access side and a public side. Members of the CoP use the limited-access side to co-write, peer-review, and manage text or visual information. In this manner, information that is viewable on the public side is reliably research-based and representative of the latest scientific consensus on the topic. In its mature state the Bee Health website is envisioned to become the most complete and authoritative compendium of literature on bee health management that science can offer.

4. EXPECTED OUTCOMES

It is to be hoped that the unprecedented degree of coordination between the two projects described here will optimize the speed with which practical improvements to bee health management can be discovered and delivered to beekeepers. We believe that the breadth of each project is appropriately broad, reflecting the uncertain state of our knowledge on the many factors interacting to impair honey bee health. At the same time, the objectives of each project seem reasonably narrow – likely, we believe, to hit close to the mark in our search for the morbidity agents most responsible for honey bee decline. Insofar as we can narrow the list of candidate agents, refine research priorities, and effectively deliver to beekeepers the best science-based management recommendations, these projects will prove a solid investment for the sustainability of America's beekeeping industry.

Réponses coordonnées au déclin des abeilles aux États-Unis.

***Apis mellifera* / déclin des pollinisateurs / CCD / syndrome d'effondrement des colonies / recherche / éducation / abeilles / *Nosema* / lutte intégrée / nutrition**

Zusammenfassung – Koordinierte Antworten auf die Abnahme von Honigbienen in den USA. Daten über imkerlich gehaltene Bienenvölker vom US amerikanischen Landwirtschaftsministerium (US Department of Agriculture, USDA) zeigen eine kontinuierliche Abnahme der Bienenvölker vom Spitzenwert von 6 Mio. in den 1940er Jahren auf 2,3 Mio. im Jahr 2008 (Abb. 1). Die vermutlichen Ursachen für diesen Rückgang sind vielfältig. Sie beinhalten trans-globale Pathogene und Parasiten und sozio-ökonomische Trends, die Imker aus ihrer Praxis drängen, was in ganz Europa der Fall ist. Zusätzlich sind unter den toten Völkern aus der jüngsten Vergangenheit eine Gruppe mit abgegrenzten Symptomen, die als „colony collapse disorder (CCD)" bezeichnet wurden. Die Hauptsymptome des CCD sind Schwund oder nahezu vollständiger Verlust adulter Bienen und ein geringer Anteil von Adultbienen zu Brut. Die generelle Abnahme der Völkerzahlen, zusammen mit einer erhöhten Mortalität aufgrund von CCD und anderen Faktoren, führte zu einer Verteuerung der Bestäubungsprämie für Mandeln und anderen Nutzpflanzen. In den Vereinigten Staaten wird der Anstieg der bestäubungsabhängigen Nutzpflanzen von einer Abnahme des nationalen Bienenvölkervorrats begleitet, eine ernste Situation für die landwirtschaftliche Bestäubung.

Als Reaktion auf die hohe Honigbienensterblichkeit der vergangenen Jahre beauftragte der US Congress das US Landwirtschaftsministerium damit, solche Forschungs- und Bildungsförderung zu steigern, die auf eine Reduktion der Honigbienenabnahme gerichtet sind. Der Landwirtschaftliche Forschungsdienst der USA (USDA-ARS) fördert ein von vier ARS Laboratorien durchgeführtes, sogenanntes *Areawide* Projekt. Das USDA National Institute for Food and Agriculture fördert ein koordiniertes Landwirtschaftsprojekt (*CAP*), welches vornehmlich von Wissenschaftlern und Pädagogen aus staatlichen landwirtschaftlichen Colleges betrieben wird. Beide Projekte, *Areawide* und *CAP*, sind durch ein Konsortium von Forschern charakterisiert, die koordiniert zusammenarbeiten, um institutionelle Redundanz zu reduzieren und die Entdeckung und Verbreitung einer nachhaltigen Imkerei zu optimieren.

Das übergeordnete Ziel des USDA-ARS *Areawide* Programms ist es, das Überleben der Völker und die Verfügbarkeit für Bestäubung zu erhöhen. Der *CAP*-Ansatz geht davon aus, dass die Bienenabnahme ein Produkt zahlreicher interagierender Faktoren ist: synthetische und organische. Daraus sollen Versuche um die spezifischen Faktoren der Völkerverluste entwickelt werden. Der Technologie- und Wissenstransfer vom *Areawide* Programm und *CAP* Programmen wird ein Gruppenaufwand mit Unterstützung des Verbandes der amerikanischen Berufssimker (American Association of Professional Apiculturists: AAPA) sein. Die auffälligste bereits lancierte Partnerschaft ist die Webseite der Gemeinschaft zur Bienengesundheit und Praxis (*Bee Health Community of Practice*, http://www.extension.org/bee_health). Es ist eine Kollaboration zwischen dem *Areawide* Programm und allen oben genannten Programmen. Beide Projekte, *Areawide* und *CAP* werden daran arbeiten, die Gesundheit der Bienenvölker zu verbessern und wissenschaftlich fundierte Lösungen anzubieten um die Bienenhaltung und das Überleben der Bienen zu verbessern.

***Apis mellifera* / Bestäuberrückgang / colony collapse disorder / CDD / Forschung / *Nosema* / Bildung / integrierter Pflanzenschutz / Ernährung**

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