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Multifactorial Declines in Global Insect Pollinator Populations – Case Studies in Honey Bees

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Abstract Global decline in insect pollinator populations, especially honey bees, is a cause of serious concern. Pollination not only ensures food security, but also maintains biodiversity of the vast floral resources across the world. Various abiotic and biotic stressors have been attributed to the detrimental impacts on bee pollinator populations. This short review will emphasize on the various multifactorial concerns affecting honey bee populations worldwide ranging from pests, pathogens, diseases, pesticides and malnutrition. These elements are often synergistic, causing reduced longevity, suppressed immune systems and increased oxidative stress in worker honey bees, to name a few instances. Malnutrition further increases honey bee susceptibility to pathogens and diseases. It is important to understand the dynamics and impacts of these environmental stressors on important pollinator populations to be able to mitigate their effects efficiently.

Keywords Pollinators, Pesticides, Nutrition, *Varroa*, *Nosema*

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INTRODUCTION

Pollinators provide a vital ecosystem service to both wild and cultivated plants, ensuring production of food crops, floral biodiversity and maintenance of insect-pollination dependent plants. Crops like strawberry, apple, almond and melons are heavily dependent on pollination for production of seed sets and approximately 70% of the 124 major food crops are dependent on pollinators (Klein et al. 2007; Gallai et al. 2009). Insect pollination ensures maintenance of the genetic diversity in wild plants (Williams and Carreck 1994). A wide variety of plant species may also provide food sources for many mammals and birds. Thus, the economic and environmental costs of global decline in insect pollinators are profound (Vanbergen et al. 2013).

Honey bees are perhaps the best studied among insect pollinators (Basu and Chakrabarti 2015). They are essential components of agriculture and many crops are completely dependent on them for pollination (Free 1993). Honey bee colonies are also a good source of revenue generation for commercial beekeepers. For example, the value of crop pollination in the United States by honey bees is estimated to be more than $17 billion (Calderone 2012). There has been a sharp decline of 61% in honey bee populations reported between 1947 and 2008 (Ellis et al. 2010; vanEngelsdorp and Meixner 2010). This is alarming to both beekeepers and growers, whose economic viabilities are interdependent.

Multiple factors are responsible for the collapse of entire honey bee colonies, as well as a significant reduction in native bee populations. This short review will focus on honey bees as the pivotal insect pollinators and will emphasize some of the important biotic (viruses, pests, pathogens etc.) and abiotic (pesticides, malnutrition etc.) stressors, which are currently held responsible for global declines in insect pollinator populations.

PESTS, PARASITES, PATHOGENS AND DISEASES

Insect pollinators, especially honey bees, are bombarded with innumerable viruses, bacteria, fungi and parasites which threaten their populations. *Ascosphaera apis* and *Aspergillus flavus* cause chalkbrood disease and aspergillosis respectively in honey bees. It has been reported that environmental variances (*viz.* rain, humidity, temperature variations etc.) accentuate these fungal infections (Mehr et al. 1978; Aronstein and Murray 2010). *A. apis* spores may contaminate foundation wax and this in turn may be the source of the infection in healthy colonies (Flores et al. 2005).

Bacterial pathogens infecting honey bee colonies are primarily *Paenibacillus larvae* and *Melissococcus pluton* which result in American foulbrood and European foulbrood infections, although, honey bees have been reported to progressively develop resistance to *P. larvae infection* as they age (Brødsgaard et al. 1998). Lesser-researched diseases include honeybee spiroplasmosis, septicemia, and paratyphoid disease caused by *Spiroplasma melliferum*, *Pseudomonas* sp. and *Salmonella paratyphi A* respectively (Morse and Nowogrodzki 1978; Mouches et al 1983; Clark et al. 1985; Evans and Schwarz 2011).

Varroa destructor mite is the primary vector for the viral infections in honey bee colonies. Viruses cause damage to the honey bee colony by affecting bee physiology, morphology and other functions (Chen et al. 2005; Maori et al. 2007; Runckel et al. 2011). There have been reports of numerous viruses (more than 20) infecting honey bee colonies (Bailey 1981; Ellis and Munn 2005; Zhang et al. 2012; Li et al. 2014), of which, the three major viral infections are: 1) The deformed wing viral infection causes morphological aberrations including deformed wings in adult honey bees (Bailey and Ball 1991). Even though this virus does not usually harm pupae, it reduces adult longevity by its independent and cumulative effects with *Varroa* mites (Dainat et al. 2012). 2) The Chinese sacbrood virus is another important viral pathogen and is reported to cause sacbrood disease in *Apis cerana* (Gong et al. 2016). This disease inhibits larval development and thereby subsequent pupation (Aronstein and Murray 2010; Han et al. 2013). 3) The Israeli acute paralysis virus is often considered

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responsible for colony collapse in the United States (Cox-Foster et al. 2007) and this has been supported by other recent studies which report similarities in colony malfunctions between Israeli acute paralysis viral infection and colony collapse symptoms (Hou et al. 2014).

Nosema ceranae and *Varroa* mites are the most commonly reported honey bee parasites producing microsporidiosis and acarine diseases respectively (Martin 2001; Sak et al. 2004). *N. ceranae* was first identified in *Apis cerana* (Asian honey bee) and was later found to expand its host range to *Apis mellifera* (Western honey bee / European honey bee). Numerous reports have attributed honey bee gut epithelial degeneration, tissue impairments, reduced longevity, increased oxidative and energetic stress in honey bees to *Nosema* infection (Antunez et al. 2009; Mayack and Naug 2009; Dussaubat et al. 2012; Wolf et al. 2014; Mayack et al. 2015). *Varroa* mites, on the other hand, feed on honey bee hemolymph causing physiological injury, suppressed immunity and malnutrition (Degrandi-Hoffman and Chen 2015). Some recent studies are also exploring fat ingestion by *Varroa* mites and the risk they pose to honey bees as a result of fat body consumption (Ramsey et al. 2019).

PESTICIDE AS A MAJOR CAUSE FOR POLLINATOR DECLINE

Even though agricultural intensification has significantly contributed to the increased food production over the past 50 years (Matson et al. 1997), land use intensification has also reduced species richness and ecosystem functioning (Flynn et al. 2009). Intensification of the land essentially indicates increased use of not only fertilizers but also various pesticides and insecticides. Even though targeted towards pests, pesticides have often been reported to impose detrimental effects on non-target beneficial insect pollinators (Desneux et al. 2007). Previous studies have attributed agricultural intensification and habitat loss, due to increased agricultural expansion, as drivers for loss in pollinator richness and abundance (Ricketts et al. 2008; Winfree et al. 2009; Potts et al. 2010). Like honey bees, crop pollination by native bees has also been reported to be on the decline due to agricultural intensification (Kremen et al. 2002). Pesticide use has often been cited as a major driver of global pollinator decline (Whitehorn et al. 2012; Chakrabarti et al. 2015 a). Exposure to pesticides can occur through multiple routes – mostly when foraging bees are exposed while pollinating agricultural fields or when contaminated nectar and pollen are brought back to the hive. Honey bee hive matrices like pollen and wax have been shown to contain significant pesticide residues (Mullin et al. 2010; Pettis et al. 2013) and chronic sublethal exposures may bring about adverse detrimental effects on the whole hive.

Many pesticides, *viz.* organochlorines and carbamates, have been reported to cause significant oxidative stress (Qiao et al. 2005; Chakrabarti et al. 2015 a). Increased antioxidant enzyme activities have been reported in honey bees in pesticide laden environments (Chakrabarti et al. 2015 a) and are often considered as potential biomarkers for oxidative stress (Badiou-Beneteau et al. 2012). An elevated oxidative stress may also be observed in honey bees when environmental exposures are coupled with migratory hive managements (Simone-Finstrom et al. 2016). Among other oxidative stress enzymes, xanthine oxidase has also been reported to increase under pesticide exposure (Chakrabarti et al. 2015 a). Unlike other insects, honey bees lack certain detoxification enzymes to counteract the detrimental effects of pesticides (Claudianos et al. 2006) and hence, pesticide toxicity is one of the major concerns for global bee declines. Commonly used miticides, *viz*. formic acid, have been reported to reduce brood survival and honey bee longevity (Fries 1991; Underwood and Currie 2003; Di et al. 2013). Indeed, regulation of acaricide treatment in honey bees has been reported to be influenced by numerous immunity-related genes (Boncristiani et al. 2012).

New studies reveal more information on the effects of sublethal pesticide toxicity on honey bees – ranging from impaired olfaction, learning, social immunity, reduced life span, foraging and hygienic behavior in honey bee workers, decreased egg laying by queens and precocious foraging in workers (Schneider et al. 2012; Henry et al. 2012; Chakrabarti et al. 2015 b; Tsvetkov et al. 2017). Behavior (avoidance and repellence) and morphology (*viz*. thickened cuticle acting as a natural barrier) may provide the first route of resistance to pesticides (Smirle 1988). However, when insect behavior and morphology are altered due to pesticides, bees are more susceptible to further toxic exposures. Honey bees, like other insects, are constantly exposed to numerous random odor stimuli which they use to synthesize substantial information. Proboscis extension response/reflex (PER) studies have been a common tool in understanding the effects of pesticides on honey bee olfaction (Han et al. 2010; Chakrabarti et al. 2015 b). Odor detection is assisted by help of olfactory receptor neurons (ORNs) called sensilla (Sandoz 2012), which are located on the antennae. A recent study has helped identify the morphological aberrations of sensilla and significant reductions in their numbers in pesticide-exposed honey bee populations by help of Scanning Electron Microscopy (Chakrabarti et al. 2015 b). Ion channel activity has a pivotal role to play in olfactory pathway in the honey bee brain (Grunewald 2003). Calcium, being the preliminary trigger for long term olfactory development (Perisse 2009), has often been studied. Pesticides have been recently reported to impede honey bee olfaction by reducing biologically active free Ca^{2+} in the two major olfactory regions of the honey bee brain – mushroom body and antennal lobe regions (Chakrabarti et al. 2015 b).

Even though in declining numbers, honey bee colonies do survive in the intensive agricultural field sites. Perhaps through developing genetic heterozygosity, these hives are able to cope with the environmental stress. In fact, metals and other pollutants, like pesticides, are reported to be absorbed by the cellular components of the physiological processes, leading to various changes including alterations of the genetic system leading to the inhibition or alteration of enzyme alleles (Dix 1981). A recent study reported that honey bee (*A. cerana*) populations exposed to pesticides over a prolonged period exhibited increased genetic diversity at both protein and DNA levels (Chakrabarti et al. 2018). The repertoire of various studies help shed light on the impacts of pesticides on honey bee populations, thereby having a far reaching effect in understanding the responses in other insect pollinator species.

NUTRITIONAL STRESS IMPACTING INSECT POLLINATORS

Poor nutrition is recently being recognized as one of the important causes for bee declines. Malnutrition in honey bees may result from a combination of factors ranging from loss in habitat, monocultures and alterations in floral phenology (Kremen et al. 2002; Naug 2009; Vanbergen et al. 2013, Otto et al. 2016). In fact, sufficient nutrition is attributed to stronger colonies with better immunity – well-nourished bees are less susceptible to *Nosema ceranae*, have lower pathogen loads, overwinter more successfully and are better able to cope with parasites, diseases and insecticides (Eischen and Graham 2008; Di Pasquale et al. 2013; DeGrandi-Hoffman et al. 2016; Jack et al. 2016, Glavinic et al. 2017; Brodschneider and Crailsheim 2010; Mao et al. 2013; Schmehl et al. 2014). Insufficient nutrition in colonies leads to physiological anomalies in emergent spring workers (Mattila and Otis 2006) and in larval stages, results in formation of ineffective foragers and selection of fewer queens in the colony (Scofield and Mattila 2015; Sagili et al. 2018). Habitat imposed nutritional stress is one of the important drivers of the recent honey bee declines (Naug 2009; Archer et al. 2013). Optimal nutrition is hence often considered the primary defense in honey bee colonies against both abiotic and biotic stressors and is crucial in maintaining healthy pollinator populations, especially in an adverse environment (Brodschneider and Crailsheim 2010).

CONCLUSIONS

With increasing decline in the abundance and diversity of bee forage, increasing exposure to agrochemicals and cumulative pressures from pests and pathogens, bees are on a steady global decline (Goulson et al. 2015). It is important to note that stressors do not act in isolation and their cumulative effects are perturbing. For instance, malnutrition increases pollinator vulnerability to parasites, pathogens and diseases. This in turn weakens them and renders them susceptible to pesticide exposures. Chronic exposures to multifactorial stressors seem to drive global bee population decline – for both managed and wild bees (Goulson et al. 2015). Incorporating flower- rich habitats into farmlands to reduce nutritional stress on bees, reducing pesticide exposures of insect pollinators through adopting sustainable farming methods and implementing effective quarantine actions

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on infected managed colonies are all practical measures that may be adopted (Chakrabarti et al. 2015 a; Goulson et al. 2015). Pollination is one of the most crucial ecosystem services of global benefit, and measures must be taken to ensure a sustainable future. Further research on the various biophysical pathways, gene expressions, habitat studies, pesticide toxicity assays and exposure mechanisms in insect pollinators can hold the key to understand methods required to offset the various biotic and abiotic stressors.

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