ASSESSING HONEY BEE EQUILIBRIUM RANGE AND FORAGE SUPPLY USING SATELITE-DERIVED PHENOLOGY

Nightingale, J.M.[1,2] Esaias, W.E.[1] Wolfe, R.E.[1] Nickeson, J.E.[1,2] and Ma, P.L.A.[1,2]

[1]NASA Goddard Space Flight Center, Greenbelt MD 20771
[2]INNOVIM, 7501 Greenway Center Drive, Suite 660, Greenbelt MD 20770

ABSTRACT

Two important and highly publicized issues regarding honey bees are impacting agricultural pollination and honey production in the United States. These are: 1) the increasing presence of the invasive Africanized Honey Bee (AHB); and 2) the spread of pests and diseases within managed European Honey Bee (EHB) populations that cause major loss of colonies (of which Colony Collapse Disorder (CCD) is the most recent). The primary objective of this research is to improve prediction of the equilibrium range of both the AHB and EHB within the U.S, and to determine the impact of both urbanization and climate change on this equilibrium range. This will be achieved through integration of: climate data; scale hive defined nectar flow measurements; nectar and pollen source distributions; as well as satellite-derived vegetation phenology.

***Index Terms*—** Satellite Phenology, Plant – Pollinator interactions, European and Africanized Honey Bees, Scale hives.

1. INTRODUCTION

Key to accurate determination of the equilibrium range of both European and Africanized Honey Bees is an understanding of the species interaction with available forage sources as well as their climatic, edaphic and environmental limits. The topic of how honey bee populations will respond to climate change and the development of new management techniques to cope with this is of great national importance. Bees are responsible for most crop pollination and are often actively introduced by farmers into crops to improve production. Commercial honey bee pollination services are a significant industry in the U.S. worth upwards of $20B annually [1]. This critical service has been compromised by the decline of beekeeping (~50% since 1950) due to diseases, loss of subsidies, and insecticide poisoning, coupled with increasing pollination demand [1,2]. The rise of Colony Collapse Disorder (CCD) in 2006 only became more critical when the spring pollination season began in early 2007 and huge numbers of colonies disappeared. CCD represents a condition that is characterized by an unexplained rapid loss of a colony's adult population. Collapsed colonies have no or very few bees remaining despite the abundance of food stores in these colonies. The stores appear to remain untouched by robbing bees or pests such as wax moths and small hive beetles for several weeks after the collapse [3]. Affected operations can be devastated by the condition and losses of up to 90% of colonies have been reported. The ramifications of such losses are highly significant given honey bees pollinate more than one-third of the food consumed in the U.S [1].

In the United States, beekeeping is likely to decline further as the Africanized race of *Apis mellifera* continues to spread northward from its introduction site in Brazil. In the southwestern United States, the AHB already hybridize with managed colonies of European honey bees, conferring an aggressive trait and creating liability concerns for beekeepers. The migration of the AHB from eastern Brazil into the southern United States since its introduction there in 1957, has been well documented [4,5]. All attempts to limit its range have been unsuccessful. The AHB has reached an equilibrium position along its southern boundary in Uruguay, presumably due to climatic and environmental limits, but it is not clear that further spread in the U.S. is precluded by environmental factors. The most recent predictions of its eventual range are based on various parameterizations of winter temperature stress and winter climatology for the U.S. and exhibit a high degree of uncertainty. Estimates of its final northern limit range from N. Florida to Central Pennsylvania along the East Coast, depending upon which climate analysis is chosen [4]. The precise prediction of its range has costly implications for how states, and the apiculture (beekeeping) community in particular, prepare for and respond to the threat.

This paper describes the first stage in our research into the use measurements of honey bee nectar flow, knowledge of pollen sources and satellite-derived vegetation phenology to better understand and predict the equilibrium range of both the AHB and EHB.

2. MATERIALS AND METHODS

2.1. Scale Hives

A scale hive is a honey bee hive that is set upon a stationary scale for the growing season so that daily or weekly readings of cumulative hive weight during nectar flow can be tracked. We utilize historic and contemporaneous scale hive weight records from various locations in the U.S. and the current volunteer observing network within the Mid-Atlantic region, Fig 1. These data sets directly indicate the periods of active nectar collection by honeybee colonies, and clearly show responses to short and mid range climatic events through timing and duration of nectar flows. Metrics to assess interannual variability and to compare with satellite-derived vegetation data were developed using scale hive records from Corvallis, Oregon from 1982-1990 [6] and a record spanning 1992-2006 from the Mink Hollow apiary in Highland, Maryland (Esaias, *Personal comm*). The six metrics are applied to weekly smoothed, normalized data and include the beginning (0.05 total gain), end (0.95 total gain), peak, midpoint (0.5 total gain), duration, and average peak. These metrics were found useful for characterizing what is termed the Honey Bee Nectar Flow (HBNF) and demonstrate that the interaction depicted reflects the specific biases inherent to honey bee foraging preferences and behavior.

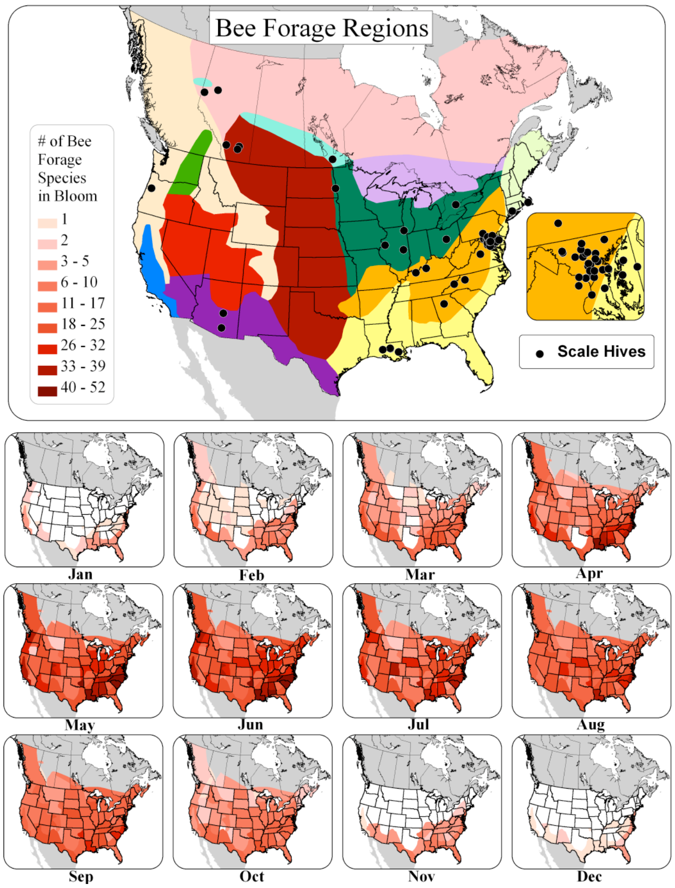

Fig 1: Bee forage regions of North America derived from Ayers and Harmon (1992) [7] showing current scale hive locations. The lower panel shows the total number of bee forage plants in bloom during each month of the year.

2.2. Nectar and pollen sources

Information on nectar and pollen sources: the species; location; duration of nectar flow; and frequency of nectar availability during the year is critical for determining the forage constraints on bee populations. We collated 14 Bee Forage regions within North America that are based on natural floristic and land use patterns as defined by [7], Fig 1. Within each region, the average blooming period of important nectar and pollen species was determined through a composite of data acquired from questionnaires sent to local beekeepers and from major published flora and apicultural botanical literature. This data will be used to map the number of plants (trees, forbs, shrubs, grasses) in bloom during each month and provide additional information on the length of available forage sources for bee communities. The maps will also be used to supplement the satellite-derived vegetation information.

2.3. Satellite derived vegetation phenology

Hive weight records provide a way to link satellite observations to pollination and ecosystem climate change. Scale hives are well suited for assessing spatial and temporal variations in nectar flows and easily relate to remote sensing because they integrate over very similar spatial scales as the satellite data and coupled model outputs. Colonies forage over a radius of from 0.5 to 10 km with a mean of about 2.3km [8]. This aspect of using scale hives and the bees themselves to sample the environment, and relating the regional metrics to satellite-derived data to reveal impacts of climate change are very novel and creative. While EHB's are analyzed in this study, the close similarity of the AHB with respect to nectar and pollen foraging makes the data relevant to both populations.

2.3.1. MODIS NDVI

One of the key phenological parameters tied to the honey bee life cycle is the blooming associated with the spring green-up. To help derive this timing so that it can be used in honey bee forage modeling and prediction, we plan to utilize satellite-derived phenological metrics. The temporal vegetation phenology, i.e. green-up and brown-down, will be assessed using the NDVI (Normalized Difference Vegetation Index) derived from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor. The NDVI is calculated as a simple ratio between measured reflectivity in the red and near-infrared bands and has evolved as a primary tool for monitoring vegetation changes and the interpretation of the impact of short – long-term climatic events on the biosphere [9]. We extracted a MODIS (collection 4) surface reflectance data subset over the Highland scale hive site in Maryland from the ORNL (Oak Ridge National Laboratory) DAAC (Distributed Active Archive Center). The subset covered a 6.5km x 6.5km region (approximately 13 x 13 pixels) and provided atmospherically corrected surface reflectance data at 500m resolution for seven years (2000 – 2006). NDVI was calculated for vegetated pixels in this region. These data were manually gap-filled and outliers were removed. For the corresponding satellite / scale hive record period, cumulative NDVI was compared to the six scale hive metrics outlined above.

2.3.2. MODIS Phenology metrics

Of special interest to this project are the time-dependent vegetation phenological metrics derived from TIMESAT [10]. TIMESAT is a software program for analyzing time-series satellite data and has been applied to four MODIS products including the NDVI, enhanced vegetation index (EVI), leaf area index (LAI) and fraction of photosynthetically active radiation (FPAR) [11]. This newly-developed set of temporally smoothed and spatially-continuous MODIS biophysical data provide ideal data sources for tracking key phenological parameters including: 1) start of the season; 2) end of the season; 3) length of the season; 4) base level; 5) middle of the season; 6) peak value; 7) seasonal amplitude; 8) left slope; 9) right slope; 10) large seasonal integral; and 11) small seasonal integral. These phenological metrics derived from the MODIS collection 4 EVI dataset at 250m resolution will be compared directly to the six scale hive metrics for each scale hive location following the procedure outlined for the MODIS NDVI comparison.

3. RESULTS AND DISCUSSION

3.1. Bee Forage Phenology

3.1.1. Maryland Scale Hive Data

Many floral species are included in the composite HBNF, but usually only a few dominate at any one time and region (Fig 1). Overall, the scale hive metrics give a very useful representation of nectar flow timing in that honey bees are generalist foragers and enable us to begin classification of the environment without having to resort to tracking the large number of blooming plants and individual species responses. The dates, modality, and duration of HBNFs vary considerably with region, climate, and floral composition. Figure 2 compares nectar flows from Tucson [12], Highland (Esaias, *Personal comm.*), and Corvallis [6]. Both Tucson and Highland show spring maxima but due to vastly different species. The Tucson hives make significant gains in August, while Corvallis has an extended summer flow, whereas Highland has a long summer dearth. Scale hive data collated at the Highland site over a 15-year time-series (1992-2007), Fig 3, shows variations due to short-term climate events as well as an overall trend of a significantly earlier spring bloom by 25 days. From this short record we can infer that nectar flow dates and quality are changing in Maryland due to climate and urbanization effects.

Comparison of peak scale hive weight to minimum temperature data for sites located in Maryland show that a one degree level of warming corresponds to a seven day advance in the HBNF during 1992 - 2007. Concerns are raised as to the effect that additional temperature increases predicted with global warming scenarios will have on plant-pollinator interactions currently observed. Impacts associated with an earlier HBNF are considerable. For example, beekeepers will find it harder to raise colonies strong enough in time for pollination and honey production, while packages of bees delivered from the South may arrive too late to replace winter colony losses. As a result, crops could suffer and costs will increase. Resulting colony stress will force expensive supplemental feeding. Poorer pollination of wild plants means less wildlife food and forage, with potential impacts to natural plant succession. Further, migratory insects and birds may arrive too late to take advantage of nectar flows. Climate change may make an area more, or less, susceptible to Africanized Honey Bee invasion.

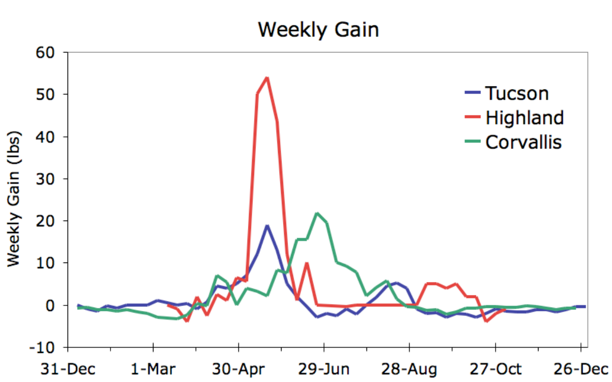

Fig 2: Nectar flows from Tucson [12], Highland (Esaias, *Personal Comm.*), and Corvallis [6]. Tucson and Highland show spring maxima but due to different species. Tucson hives make significant gain in August, and Corvallis has an extended summer flow, whereas Highland has a long summer dearth.

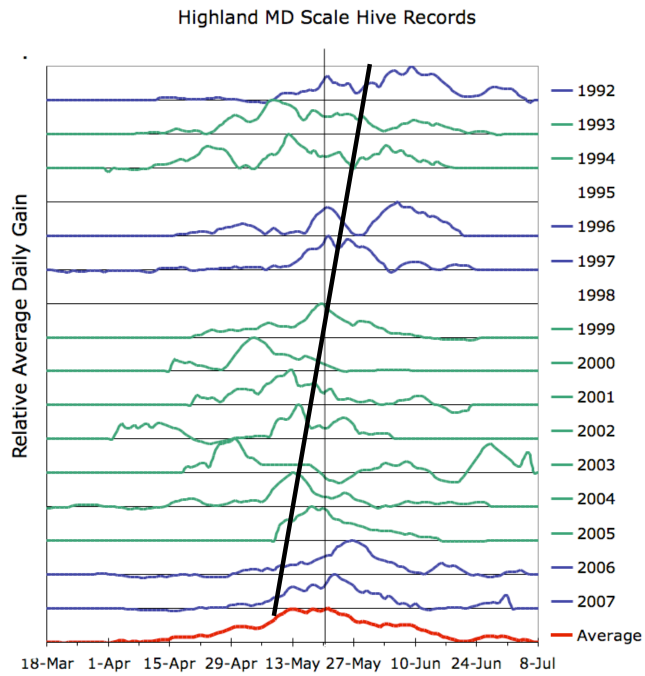

Fig 3: Scale hive data collated at the Highland site over a 15-year time-series (1992-2007), show variations due to short-term climate events as well as an overall trend of a significantly earlier spring bloom by 25 days. Green lines represent years with a nectar flow peak earlier than the average, while the blue lines represent years with a nectar flow peak later than the average.

3.2. Can satellites track the HBNF?

3.2.1. Vegetation phenology from AVHRR NDVI

A recent study by [13], analyzed vegetation phenology derived from a 24 year time-series of AVHRR (Advanced Very High Resolution Radiometer) NDVI data (1982 – 2005) for North America. The weekly composite data were available at 4km resolution. The trend of interannual variation in green-up onset was calculated using a simple linear regression slope for each pixel. This analysis provided information on the interannual change rate in greenup onset for this period, where negative values represented an advanced trend and positive values denoted a delay in greenness onset. We compared the scale hive information for the Highland site to the greenup onset change rate provided by [13]. The scale hive at the Highland site showed an advance in the peak HBNF of -0.56 days per year, corresponding directly to -0.57 derived from the NDVI time-series. Further validation of this AVHRR product will be conducted when all of the scale hive datasets (Fig 1) have been collated and analyzed. It is interesting to note that in this study, not all areas of the United States will exhibit earlier vegetation greening and hence an earlier HBNF. Improved information regarding the greenup dates across North America are critical not only for migratory beekeepers and crop production, but the fate of all plant-pollinator interactions.

3.2.2. Vegetation phenology from MODIS

We calculated averaged and cumulative NDVI for a 6.5km x 6.5km subset representing the forage region around the Highland scale hive site. Table 1 shows the association between five measured scale hive metrics (duration is not calculated) and the computed NDVI. MODIS NDVI predicts the average peak and mid-point nectar flow at this site (R^2 0.79 and 0.80 respectively, $p < 0.05$) over the analysis period, but does not prove a strong predictor of the beginning of the nectar flow.

Scale hive metric	MODIS NDVI	MODIS EVI phenology
Peak	0.77	0.57
Average peak	0.79	0.52
Beginning (0.05)	0.65	0.30
Mid point (0.5)	0.80	0.63
End (0.95)	0.11	0.05

Table 1: Association between scale hive metrics and cumulative MODIS NDVI and EVI phenology metrics for the Highland site, 2000 – 2006.

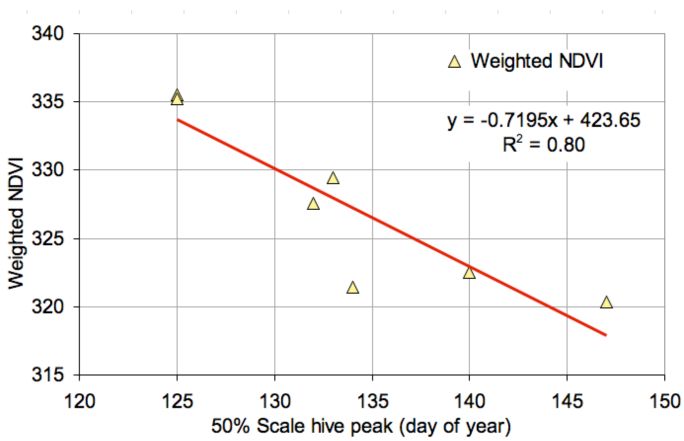

Figure 4: Association between the mid-point scale hive weight and weighted cumulative MODIS NDVI for the Highland site, 2000 – 2006.

We compared the metrics from the MODIS EVI phenology product to the scale hive data at the Highland site, Table 1. These metrics do not perform as well as those derived with NDVI. This may be due to the smaller integrated forage sample size (1km x 1km, 3 x 3 pixels) surrounding the site. Both the NDVI and EVI phenology metrics will see a noticeable improvement from the current collection 4 to the re-processed collection 5 products. This data will become available in the coming months and the relationships between the scale hive metrics and satellite derived vegetation phenology will be revisited.

4. FUTURE DIRECTIONS

We are developing a continental network of scale hives and satellite vegetation indexes to begin to study the impacts of climate change on plant-pollinator interactions. From this, the association of scale hive metrics to the improved collection 5 MODIS phenology metrics will be assessed. We are in the process of collecting and collating both historic (pre-satellite record) and current scale hive records across North America and endeavor to use the plant-pollinator information gathered to map the suitable AHB habitat across North America. These suitability maps will be based on current county-level AHB presence information, as well as climate data and information on available bee forage and plant phenology derived from the satellite time-series. For more information and updates on this research, please visit our webpage, HoneyBeeNet:
http://honeybeenet.gsfc.nasa.gov/

5. ACKNOWLEDGEMENTS

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