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The objective of this study was to investigate the possible correlation between honey production in *Apis mellifera* hives and vegetation health and greenness as well as other measurements of the surrounding environment, such as precipitation and land use. Specific focus was placed upon the use of the Normalized Difference Vegetation Index (NDVI), a satellite-imagery derived index of vegetation strength, as an indicator of vegetative nectar supply to hives.

The NASA program HoneyBeeNet furnished the dependent variable, mass records of hives in the mid-Atlantic region for four years (2008 to 2011). Using a Geographic Information System (GIS) software package, precipitation data were selected, land use statistics were derived, and NDVI values were extracted from satellite imagery in an area surrounding each hive location. Additional metrics were derived from this information using a simple statistics package.

Patterns in NDVI values at the start of the honey production season were observed, most notably an NDVI threshold below which hive mass gain will not outpace hive mass loss. However, the results indicated that NDVI and other expected indicators show little linear or multivariate correlation with honey production mass in *Apis mellifera* hives within the study at any level of appreciable statistical significance.

RELATION OF HONEY PRODUCTION IN APIS MELLIFERA COLONIES

TO THE NORMALIZED DIFFERENCE VEGETATION INDEX

AND OTHER INDICATORS

by

Bradley Carl Lynn

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Approved by

____
Committee Chair

APPROVAL PAGE

This thesis has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

Committee Chair ______________________________
Dr. Roy Stine

Committee Member ______________________________
Dr. Zhi-Jun Liu

Committee Member ______________________________
Dr. Paul Knapp

____
Date of Acceptance by Committee

____
Date of Final Oral Examination

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CHAPTER I

INTRODUCTION

The impact of spatial elements relating to honey production within European honeybee (*Apis mellifera*) colonies is poorly understood. Climate, available nectar-bearing plants, hive size, and other factors such as these that influence a hive's honey production have been identified; however, based upon this author's review of the literature, little as of yet has been done to identify how these elements and their variance over space influence honey production.

Demand for high-quality honey is increasing, yet the reported number of producing colonies in the United States is declining (vanEngelsdorp and Meixner, 2010, S81). Areas within the United States suitable for hives oriented towards honey production continue to decrease with increases in urban and suburban areas, which frequently place restrictions on beehive use (vanEngelsdorp and Meixner, 2010, S90). Furthermore, hive colony collapse disorder and other diseases are an ongoing problem apiculturalists must manage. There is a growing demand for "local" and "organic" food products in metropolitan areas, with honey included (USDA ERS, 2012). Honey production is an industry which nets 1.25 billion yearly within the United States (vanEngelsdorp and Meixner, 2010, S80); it is possible to expand both supply and profit in the domestic honey market. Specifically, a more nuanced placement of hives based upon prime nectar-bearing locations and informed management of commercial honey supplies may be an operative strategy absent significant increases in active hives.

Honey yield has long been considered to be a function of seasonal conditions, the strength of a hive, and the strength of surrounding nectar-bearing flora, especially during the foraging season; typically identified as March to October in the Northern Hemisphere, with different regions showing especially strong production at different times throughout this period (Ayers & Harman, 1992). The link between hive population and honey yield has been quantified, showing a nearly linear relation (Bhusal & Thapa, 2006). However, the exact relation between floral strength and honey yield has not been established. If one assumes hive strength to be invariable, honey yield should be expected vary from hive to hive in direct relation to fluctuations in the strength of nectar-bearing flora and local climate phenomena. Variations in vegetation strength and climate phenomena vary spatially and may explain under-performance in hives that are hypothetically identical in health and strength to other more well-performing hives.

Apis mellifera produce honey by collecting nectar from the plant blooms surrounding a hive. As such, availability of nectar is one of the limiting factors of honey production within a hive. Here I posit that nectar availability is at its peak during the greener periods of spring in which vegetation becomes and continues to be more robust; a period marked by the blooming of primary nectar plants: *Trifolium*, *Populus*, and *Cirsium* (clover, poplar, and thistle), that begins in April and lasts through mid-summer based on species type (Ayers & Harman, 1992). In short, bloom abundance coincides with the emergence and persistence of leafy green vegetation and thus a remote measurement of leafy green vegetation (by NDVI) can potentially serve as a proxy measurement of available nectar.

Satellite imagery can measure leafy green vegetation at broad scales that are not feasible when using conventional surface measurement techniques. Such remote sensing products record the intensity of reflectance within various wavelength bands of the electromagnetic spectrum, providing an image of Earth including bands outside the visible light spectrum. Using the red and near-infrared intensity values from these images a Normalized Difference Vegetation Index (NDVI) value can be calculated, which is an indexed measure of the strength and abundance of leafy green vegetation within expanses of the image. A conceptual model of the preceding statements is shown (Figure 1).

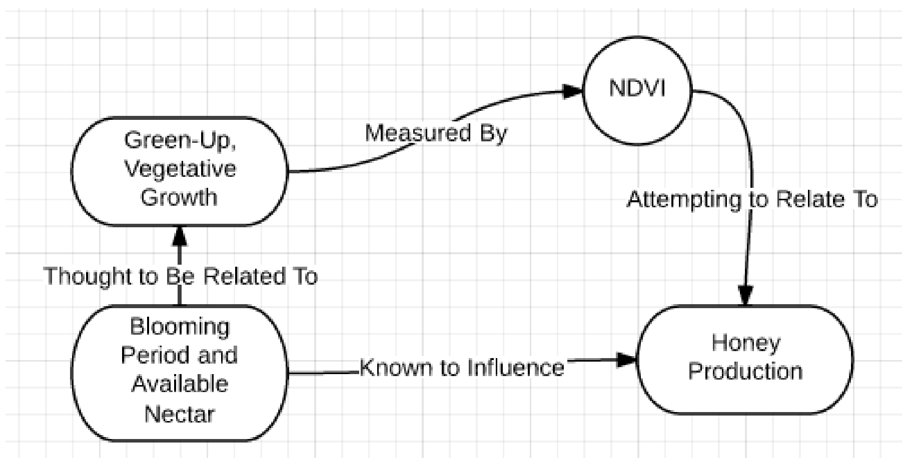

Figure 1. Conceptual Model for Relation of NDVI to Honey Production.

My thesis work will examine the null hypothesis that increased green-up and vegetative health does not correlate to honey production in *Apis mellifera* colonies. Additionally this thesis will address the following specific goals (1) the use of NDVI as an indicator of vegetative strength, (2) the use of secondary factors (precipitation, land use) in predicting honey production, and (3) determining if there exists a distinct seasonality to the relation between vegetative strength and honey production.

H^0: There is no relation between vegetation robustness (as indicated by NDVI values) and honey production in Apis mellifera colonies.

If this null hypothesis is rejected, the efficacy of NDVI as both an estimator of honey production in honeybee colonies and nectar abundance in leafy vegetation can be determined. The attempt to disprove the null will be aided by the following statistical processes: 1) an examination of the nature of the data collected using descriptive statistics and threshold values observed in independent variables as they relate to honey production, 2) a linear regression analysis attempting to link independent variables with honey production (including the use of logarithmic transformation of all said variables), and 3) an attempt at multivariate correlation analysis.

A number of smaller null hypotheses support the overall null; the dismissal of these will contribute to the reliability of the results regarding the primary null hypothesis.

Sub-hypothesis 1: H^0: Within the design of the study, NDVI is not a reliable indicator of vegetative strength.

Sub-hypothesis 2: H^0: There is no relation between any measure of precipitation and honey production in Apis mellifera colonies.

Sub-hypothesis 3: H^0: There is no relation between the amount of vegetated land-cover within an Apis mellifera colony's range and its honey production.

Sub-hypothesis 4: H^0: An NDVI-honey production relationship does not differ over different periods of the year as studied in this thesis.

As the entire honey production season (April – August) may show large variability (Ayers & Harman, 1992), my analysis will additionally include a piecewise analysis in an attempt to examine if any distinct seasonality exists in regards to the relation between vegetation strength and honey production. Initially all observation data will be analyzed according to year in order to determine the existence of a yearly variation in values. As this study will expand the understanding of how NDVI relates to expected honey production in both the spatial and temporal analysis-space, data will be separated into 2-month periods for this analysis.

The geographic scope of the study includes the mid-Atlantic region, consisting of Maryland, Virginia, Pennsylvania, New Jersey, West Virginia, and Washington D.C. This area is consistent in terms of the primary nectar sources it provides to honeybee colonies (Ayers & Harman, 1992), while still exhibiting variation in terms of other geographic properties such as elevation and prevailing land-use type.

CHAPTER II

LITERATURE REVIEW

Much work has been done in estimating what factors affect the production of honey in an *Apis mellifera* hive. Many studies concentrate upon the relation between weather conditions and daily honey bee activity over the short-term of a few days rather than an entire season. Studies from the mid-20th century attempted to link intensity of honey bee activity to sunlight hours and nectar concentration in plants, coming to the conclusion that both exhibit limiting factors on activity with other factors held constant (Butler & Finney, 1941, 1945). A later study (Vicens & Bosch, 2000) confirmed that sunlight duration and wind speed were limiting factors upon honeybee activity and reduce honey production capability.

One study looked at hive production and activity in the long term and found that honey production relates strongly to the population and weight of the hive observed hive populations, attempting to link populations of workers in a colony to yearly honey yield in areas of Alberta (Zabo & Lefkovitch, 1989). Hives from two sites were sampled twice a year in regards to their "brood area" (the amount of comb covered by soon-to-be-spawned bees) and colony population. The samples, taken in 42-day intervals during the peak production season, were compared against the honey production of each hive and analyzed statistically. It was found that the size of the colony-to-be-hatched during the key period of production had the greatest impact upon overall honey yield for a given year. Other cross-metrics including hive queen age and the drone-to-worker ratio had little correlation to honey production (Zabo & Lefkovitch, 1989).

McLellan (1977) attempted to develop a polynomial relationship between the tare weight of a colony, as collected by a scale hive, and its honey yield. This study asserted that honey within a hive could be determined by the overall weight of the colony and how far into the nectar-gathering season this weight was recorded. The resulting polynomial varied based upon season; however, during the nectar-gathering season the polynomial equation accounted for 99% of the variation between honey mass and hive weight. This study further recognized that the trends in weight gain, although explained by a polynomial, occurred at different times for different geographical locations. Beyond a casual observation that gains occurred later and greater inland than they did on the coast and speculation as to why the trends exist spatially largely due to weather, no other attempt was made to address this geographic difference.

With the advent of honeybee worker recruitment dance interpretation (Frisch, 1967) came a spate of work on hive-level details of resource collection, (an inherently spatial affair, as direction and distance from a hive can be inferred from these dances). A study from Waddinton et al., (1994) interpreted dances to determine what differences there were between recruitment systems in *Apis mellifera* hives situated in areas characterized by differing land-cover patterns (forested areas and suburban areas). The reasoning of the authors was that flowering plants are more abundant in suburban areas due to landscaping and gardening, thus the foraging strategies of the hives may change as a result of the dearth of nectar sources. Observation hives were used in two suburban locations to record and decode honeybee recruitment dances, from which the location of foraging sites could be determined. The data for suburban foraging and recruitment patterns were compared against data for forested areas from an earlier study. The authors found that bees in the nectar-abundant suburbs were less likely to follow typical recruitment systems found in forests where resources are scarce and more cooperation among hivemates is required to achieve a net gain in energy. However, the distributive spread of the forage recruitment coordinates become more patterned and concentrated in times of less abundant nectar flow, such as in late winter or early spring, which lends credence to the theory that cooperation among bees becomes more necessary in harsher environments. Thus, at macro-scales bees may develop rational and efficient methods of maximizing nectar extraction despite environmental deficiencies (Waddinton et al., 1994).

A study interpreted honey bee dances to determine direction and distance from a hive a foraging group (Beekman & Ratnieks, 2000). The study, carried out during the blooming period of nearby heather moors, found that when recorded dances of bees in a hive were decoded on foraging days and plotted upon radial maps these maps showed the frequency of nectar reports by bees, and by extension, the amount of foraging from the hive occurring in a given area. Beekman & Ratnieks (2000) found that bees were willing to travel up to ten kilometers away from the hive provided that a more abundant nectar source was locally unavailable. The study breaks into the energetics of the hive, in which the energy consumed by traveling this distance must be significantly less than the energy gained from collecting nectar in the faraway area. Also immensely interesting is the observed changes in foraging patterns observed over time. If a good source of nectar exists close to the hive, nectar is collected at this location rather than one far away. Only when foraging options are poor does long-range collection become a viable option for a hive. Thus a more varied environment with small patches of plants yielding nectar at different periods throughout a year may be more advantageous than environments with large mono-cultural patches that yield massive amounts of nectar in only one period, leaving bees to forage further at other times in order to collect nectar from different plants (Beekman & Ratnieks, 2000).

A follow-up study (Beekman et al. 2004) examined the impact that differences in the size of the hive have upon the foraging distance and foraging location of hive workers. A single hive was split into four hives, two large hives (21,000 bees and 18,000 bees) and two small hives (approximately 6,000 bees). Queens were provided for stability, and the study was conducted before the first brood of the new queens hatched (a 21 day period), thus ensuring all four hives to be nearly genetically identical. Dances occurring on six days throughout this 21 day period were recorded and decoded, four in a period of resource abundance, and two in a period of resource scarcity. Both small and large hives were statistically similar in their forage distances during all days except those characterized by resource scarcity, when the larger hives foraged significantly further than small hives. These findings reinforce those of Waddington (1994), who found that foraging distances were less for all hives when resources were abundant. Interestingly, the number of "patches" foraged by both large and small hives was similar on all days despite the disparity of workers active in each hive. Thus, unless hives are located in areas of extreme resource scarcity, bees can be expected to forage approximately the same distance regardless of colony population (Beekman et al., 2004).

While the use of worker recruitment dances to infer spatial operations of bees has been common in early 21st century literature regarding the nectar-gathering operations of bees, literature on the use of GIS and remote sensing technology to estimate honey production and yield in *Apis mellifera* colonies is sparse. If, as many of these studies suggest, landscape and location are influential in the activities and honey production in hives, GIS technologies may prove useful in analyzing landscapes in regards to their honey production potential. Most factors that can be used to predict honey production have only been defined in literature in non-spatial terms; these studies only examine hives in a single study area. However, a search of the current literature addressing applications of spatial data to honey production includes a few notable results.

Transect sites in high-elevation areas in New Zealand in order to determine influencing factors causing *A. mellifera* to forage on toxic sap were examined (Robertson, Edlin & Edward, 2010). The authors utilized three nearby weather stations to determine the spatial foraging patters of bees as related to changes in precipitation. Perhaps most important is its conclusion that honey production is a function of not only the interactions between weather and bees or plants and bees, but a three-way interaction between bees, weather, and plants.

Sande et al. (2009) inspected honey yields of apicultural sites in Kenya as they related to the distance from forest reserve zones. 300 hives recorded over 3 years were observed and the distance from the nearest stand of forest reserves measured. The study found a statistically significant increase in honey production in relation to the proximity to forests; attributing the increase to increased accessibility to diverse nectar flows. The study concludes that plant diversity within the range of a hive may increase availability of nectar over the harvest year, but makes no effort to quantify available nectar-bearing plants over a time scale.

Lastly, the primary inspiration for this thesis work: research from 2008 integrating data from *Honey Bee Net* (a NASA project which collects scale-hive data from volunteer apiculturists nationwide) and MODIS-derived NDVI data. The focus of this particular study was to (1) determine the potential for the further spread of Africanized honey bees from their current equilibrium range and to (2) determine the correlation between these shifts and environmental trends in the form of urbanization and climate change. Climate change is of special interest to the authors as they posit that earlier spring blossoming events that weaken domesticated hives in regards to available total honey stores at the end of the season, making them more susceptible to invasion from Africanized honeybees. Africanized honey bees are of concern to apicultiuralists as they are markedly more aggressive than other strains of honey bee; this aggressive trait can become a danger and liability to beekeepers. NDVI data were used to predict peak and mid-point nectar flow at given sites in an attempt to determine the timing of the overall seasonal nectar flow (Nightingale et al., 2008).

CHAPTER III

METHODS

Data Acquisition & Assessment

HoneyBeeNet

The basis of this study, used to establish honey production figures, HoneyBeeNet is a series of scale-hive observations collected by NASA's Goddard Space Flight center. These data recorded the changes in the weight of *Apis mellifera* hives in the United States over the course of a growing year. Data in the program have undergone quality assessment; any hive records that exhibit anomalies such as failures or swarming events (as indicated by a mass loss of three pounds or greater in one day) were marked as low quality and removed (Esaias, 2012). Observation periods vary between scale-hive locations, however, the majority of observations occurred from 2008 to 2011. Geographically speaking, the largest number of sites for which reliable records exists are within the mid-Atlantic region. The geographic location of each scale-hive has been recorded; this locational data allows for the study of the surrounding area. A photo of one of the scale hives used and observations reported from a scale hive are shown below (Figure 2).

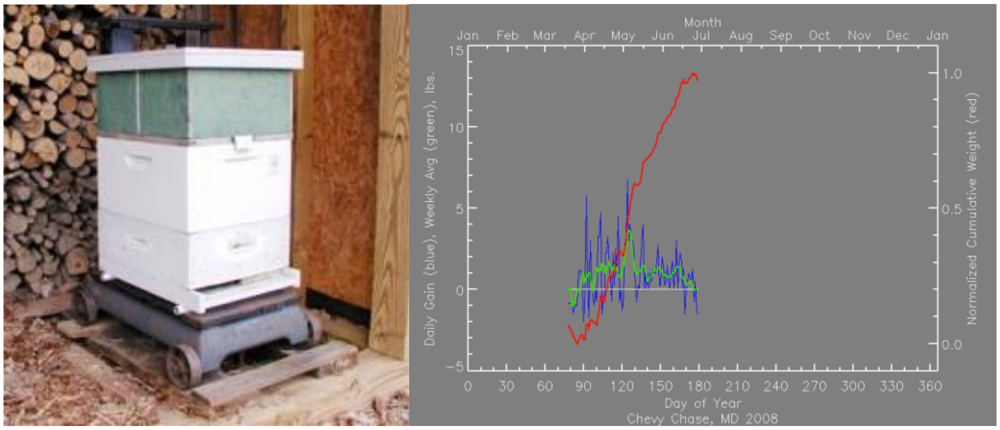

Figure 2. An Example Scale Hive and HoneyBeeNet Metrics. As provided in graphical form on the HoneyBeeNet webpage.

The publicly available locations of the hives are precise to one tenth of a decimal degree, in an attempt to respect the hive owner's privacy (Esaias, 2012). However, such precision was not suitable for the purposes of this study. Thus a request was made to officials at NASA for the use of more exact hive locations. This request was passed to individual hive owners who then allowed or disallowed use of their hives in the study. Approximately 50 sites within the mid-Atlantic region granted permission of use of geographic data accurate to the thousandth of a decimal degree (Figure 3). As privacy remains a concern for all participants, no hive coordinates of any sort will be published at any time during the study or within resulting products. Daily change in weight, a rolling seven-day average of change in weight, cumulative weight and the corresponding Julian date are provided in Comma Separated Value format on the HoneyBeeNet site for public perusal; these figures were used to derive honey production values for use in the study.

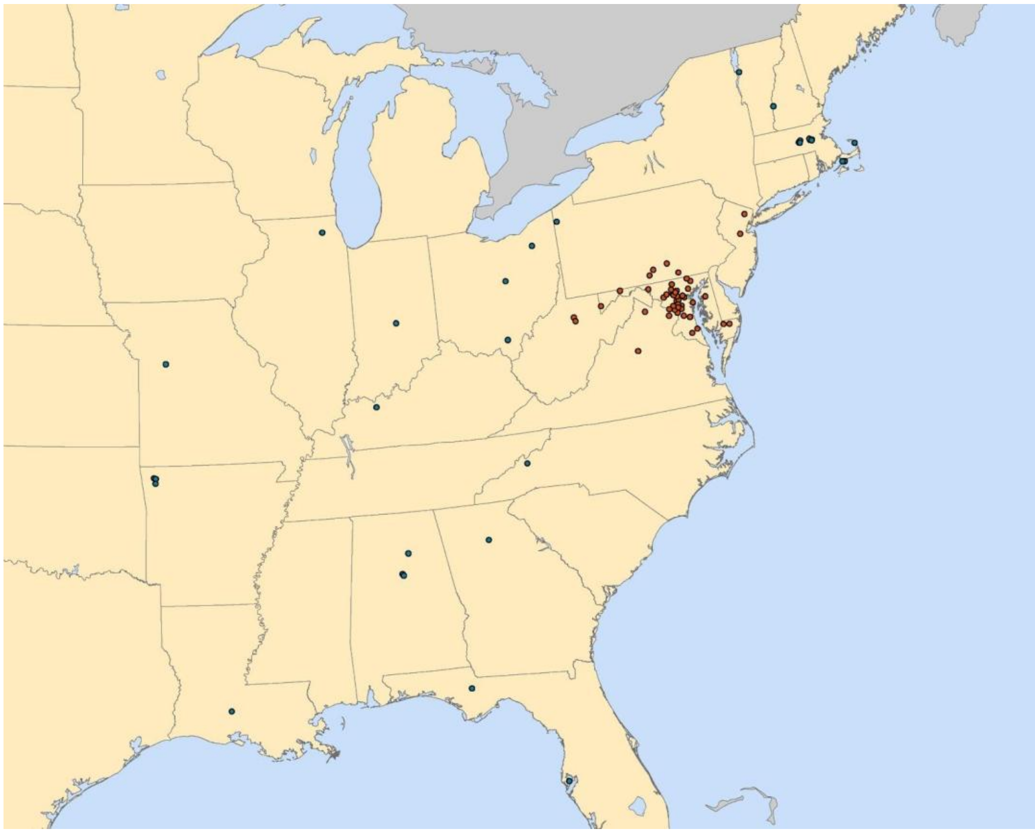

Figure 3. Schematic of HoneyBeeNet Sites that Volunteered Information. Sites included in this study are shown in orange.

Additional sites outside of the study area (the Mid-Atlantic region) also granted permission of use in this study, however these sites were deemed too few and too different from those in the study area to be of particular use. Sites determined to be within the study area were then analyzed for incongruences within the set in regards to record periods. Sites with observations before 2008 and no further observations were thrown out of the analysis, as observations in years before 2008 were too few to justify analysis. The earliest observation date out of all permission granting sites was April 16th, 2000 (at Highland, MD). Elevation within the set ranges from 5 feet to 2470 feet above sea-level, with the average elevation being approximately 462 feet above sea level.

Each site was marked with a QA (quality assessment) code by HoneyBeeNet administrators, who have taken into account the accuracy and utility of each series of site-year observations. If a site did not record mass fluctuations indicative of a major disruptive hive event (robbing, swarming, or failure, for example) and the records cover the greater part of the honey producing season, it was typically considered to be passable and received a quality assessment code of “A”. For this study, only records with “A” level data were used. While this reduces the population size of the study, it ensures that only the most accurate and consistently collected relevant data were used in the study, reducing the chance of error caused by the HoneyBeeNet data. A table of all “A” level data is shown below, complete with record date ranges in each year’s honey producing season.

Table 1. A Schematic of Available “A-level” HoneyBeeNet Observations. Each colored cell represents 16-day increments over the primary nectar collecting period of the season for one site.

	2008									2009									2010										2011								
SITE ID	113	129	145	161	177	193	209	225	241	113	129	145	161	177	193	209	225	241	97	113	129	145	161	177	193	209	225	241	113	129	145	161	177	193	209	225	241
DC001																													4	.	.	.	.	.	.	.	.
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MODIS MOD13Q1

MODIS MOD13Q1 is an image product of the Moderate Resolution Imaging Radiospectrometer (MODIS) sensor aboard the TERRA satellite. The MOD13Q1 product, which is released every 16 days, is an average of calculated Normalized Differential

Vegetation Index (NDVI) values based upon atmospherically corrected images collected over the most recent 16-day period. It features an image in sinusoidal projection with a spatial resolution of approximately 250 square meters to one pixel. The size of a single MOD13Q1 scene is approximately 10 degrees of latitude and longitude. The whole of the study area is covered by three MOD13Q1 scenes: h11v05, h12v04, and h12v05, where "h" corresponds to the row of data and "v" corresponds to the path (Figure 4). Data are available with no temporal interruption from MOD13Q1's introduction in February 2000 to the current date of this writing (USGS LPDAAC, 2011).

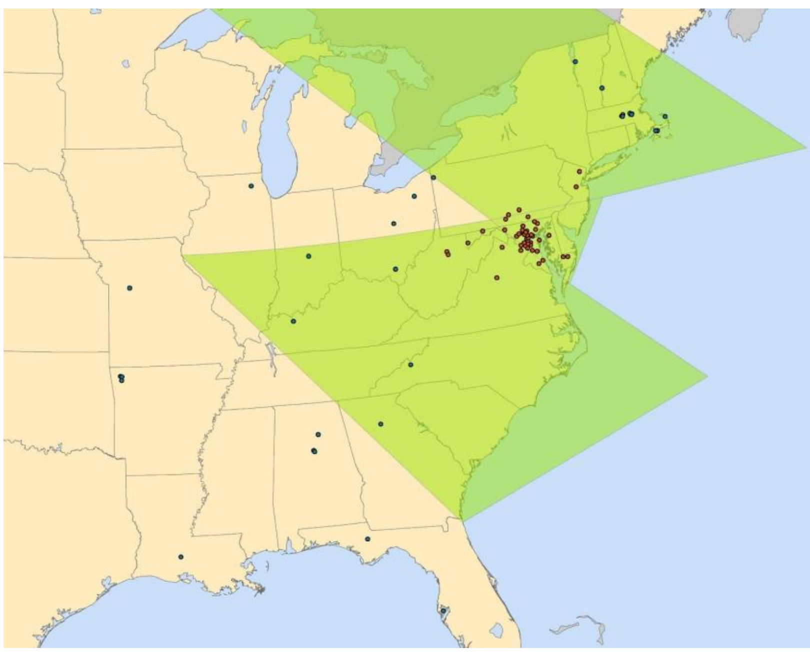

Figure 4. Extent of Three MOD13Q1 Products Relevant to the Study Sites.

The NDVI values presented in MOD13Q1 range in value from -.2 to 1 (with -.2 being the minimum value recorded within the data used; NDVI values typically range from -1 to 1), with a filler value of -30,000 used to represent areas without relevant data (oceans, bays, etc.). The NDVI data are accurate to one ten-thousandth of a decimal. NDVI has been a proven measure of vegetative robustness, derived from the red and near-infrared bands of radiometric sensors (Rouse, 1974). Figure 5 exhibits a single complete MOD13Q1 NDVI image product, wherein lighter areas of the monochrome image data correspond to greater NDVI values.

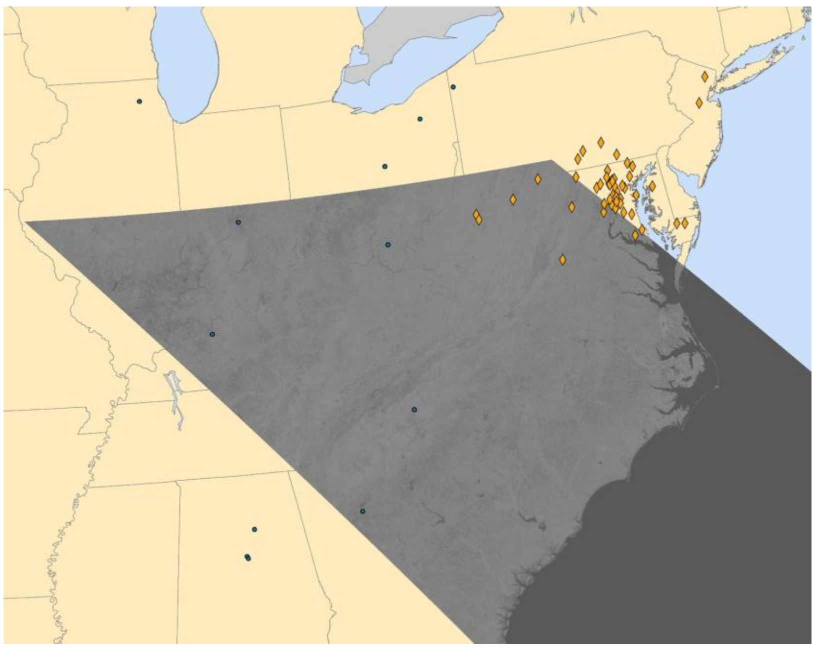

Figure 5. A Sample of a Single MOD13Q1 NDVI Product. From June 25, 2008.

Supporting Data

The 2006 National Land Cover Database is a dataset created by the US Department of the Interior. It is a national raster describing land use and land cover types in the continental United States conveyed with pixels at a 30 meter resolution. The set differentiates between many types of land cover, such as different densities of urban development and different classes of vegetative cover (deciduous, evergreen, shrubland, etc.); for the purposes of this study the raster was reclassified and used to determine a simple classification of vegetative, non-vegetative and transitional areas. This classification was then aggregated to classify the 250 meter pixels in the MOD13Q1 dataset.

L1T is an image product created from the Thematic Mapper sensor aboard the Landsat 5 platform. It is a Level 1 finished data product consisting of corrected and georeferenced imagery in seven recorded bands ranging from blue visible light to thermal waves. These data are not an average of observed values like MODIS data, but instead instantaneous observations, thus atmospheric effects such as clouds, shadows, and haze are left intact. Landsat has a return period of 16 days, meaning a single snapshot of ground conditions in a given scene are available 16 days apart from another in the series. These data were used to determine the amount of land-use change that the study area had undergone in the four-year period under scrutiny. This was done under the reasoning that a lack of appreciable change would allow reasonable use of the USDI NLCD dataset as a constant determinant of a "vegetative, non-vegetative, etc." designation used in the final analysis. Scenes were selected based upon the time of year relevant to the study (mid-spring) and relative lack of cloud cover, which is unfortunately common in LANDSAT images. This issue of cloud cover is the primary reason this study favored use of cloud-free MODIS imagery over Landsat images for use in determining NDVI.

The Community Collaborative Rain, Hail & Snow Network (from this point forward referred to as CoCoRaHS) is a precipitation record product from the Global Historical Climatology Network, a network of climate summaries in daily and monthly form maintained by NOAA. As the name suggests, community volunteers provide these records;

making the records more spatially abundant, if not accurate to the level of professionally run weather-monitoring stations.

Sites from within the CoCoRaHS-Daily set were selected based upon their proximity to HoneyBeeNet sites. After collecting the location data of all precipitation monitoring sites within the study area using the NCDC map query tool, stations were then selected in a GIS by finding the closest station by Euclidian distance to each one of the subject hives in the HoneyBeeNet dataset. This was done by using the HawthsTools (for ArcMap 9.3) extension function "Distances Between Points (Between Layers)". The resulting attribute table was used to select the precipitation monitoring stations closest to hive sites. Certain hive sites shared a closest possible monitoring station.

The sites were inspected to ensure the date ranges available matched the ranges of the study period (2008 – 2011). If sites did not have precipitation data for the study period's date range, they were thrown out and the next-closest site in order of Euclidian distance was examined. This process was repeated until all hive sites had a corresponding precipitation monitoring site: the closest possible site with complete observation data for the study period.

Spatial Processing

After these data were downloaded and organized, spatial processing was executed according to the developed workflow (Figure 6).

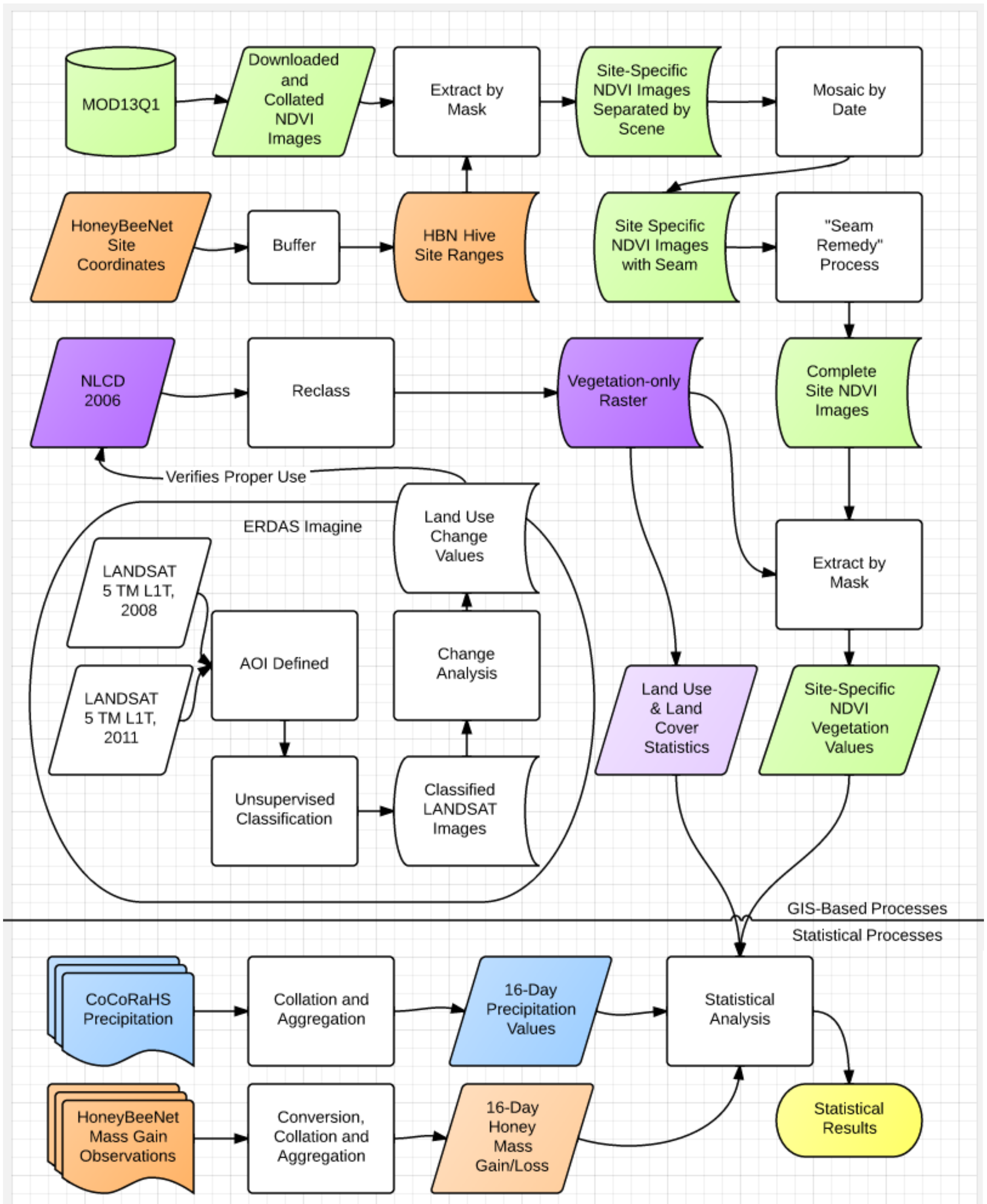

Figure 6. Flowchart Illustrating the Study Workflow.

Using a table of date-ranges needed for each MOD13Q1 scene, MODIS images were downloaded from a government FTP service known as the MODIS Data Pool. After acquisition the images were loaded into ArcGIS 9.3 and were subset to the areas of interest in the study, a circular area 10 miles in radius around each hive. This generous radius allowed for both the planned image analysis range of four miles, considered to be a reasonable maximum foraging range for hives under normal circumstances (Eckert 1933, Beekman & Ratneiks, 2000) as well as any other analysis ranges that may have been necessary to undergo at a later date. Having all images subset greatly reduced the computer storage space required as well as the computing resources and time required when loading and analyzing images.

The images were mosaicked to create a single raster file containing all three MODIS scenes for one date, in effect covering all sites in the study. Unfortunately, there existed a small seam where scenes had been mosaicked together. This seam was a one pixel wide line of no values running between the former scenes. This was remedied by loading all composite images into ArcMap 9.3 and running the "Boundary Clean" function available in the Spatial Analyst tool set. This moving window operation created an average value for a pixel based on the surrounding eight pixels in an image, thus replacing the "no value" pixels in the seam with an average value from the surrounding pixels. The resulting seam-free image was then added back to the original composite NDVI images by way of the "Mosaic to New Raster" function. Thus a new composite image with the original pixel values of all existing imagery and average pixel values for only the seam was created (Figure 7).

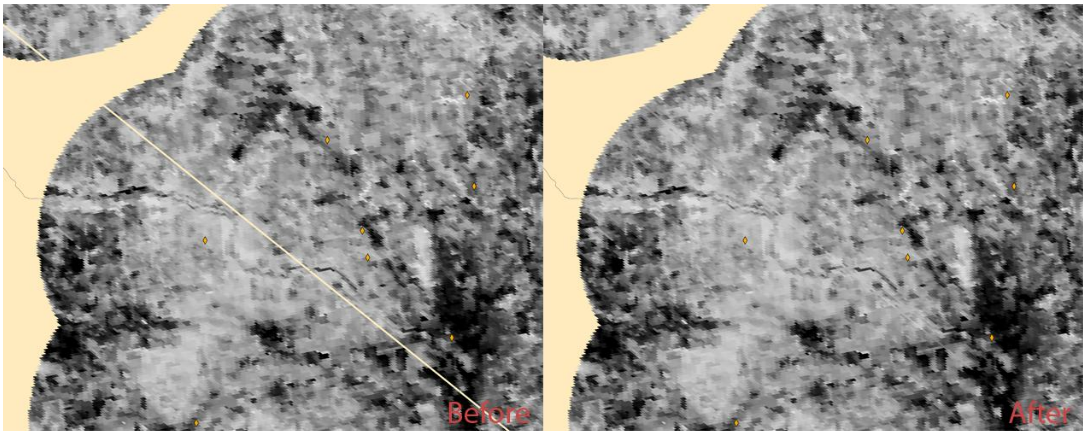

Figure 7. MOD13Q1 NDVI Subset Before and After Seam Remedy Process.

Land Use Change Assessment

An unsupervised classification was executed (in ERDAS IMAGINE 2011, unless otherwise noted) using a single scene (the area of an image product) from Landsat 5's Thematic Mapper (also referred to as TM) sensor product L1T. This single scene covers most of the study area; use of one scene simplified the analysis, as no image mosaicking or normalization across multiple images was necessary. The first image, captured in May of 2008, is completely cloudless. The second image from July of 2011 features scattered clouds in the periphery of the image. As the cloud cover can greatly affect the unsupervised classification process, the images were cropped to an area of interest featuring the metropolitan DC area and surrounding cloudless suburban and rural areas of Virginia and Maryland. This AOI creation had the added benefit of removing the borders of the image, which in Thematic Mapper scenes can be distorted or incomplete; this distortion would negatively affect the classification process. The bands of the images were stacked (one stack for each year inspected), excluding the thermal band (Band 6 of Thematic Mapper images) and then cropped using the "Subset" tool in conjunction with the previously created AOI. The images, complete with AOI border, are shown below (Figure 8).

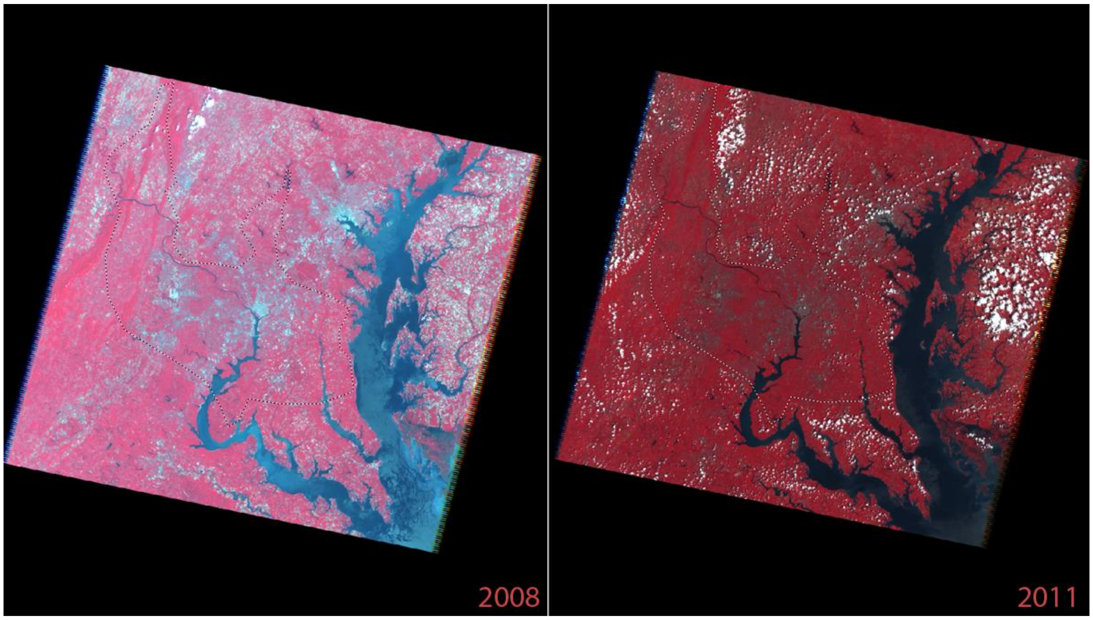

Figure 8. False Color TM Images Used in Land-cover Change Analysis. Note the clouds in the 2011 images and the AOI border that serves to exclude the majority of clouds.

A principal component analysis was executed on the images in an attempt to combine the most useful information from all bands into one or two bands to be used in the classification process. In doing so, much of the correlative "noise" from multiple bands was reduced, resulting in a more accurate classification process. This was done using the "Principal Component" function; principal component layers with float values were requested as the final result of the PCA. The resulting eigenvalues showed that nearly 93% of the variance in the bands was conveyed by the first two components in the 2008 analysis, and over 94% of the variance conveyed in the first two components of the 2011 analysis.

Based on these values (Table 2), the first two principal component bands of the resulting layers were kept for further processing.

Table 2. PCA Eigenvalues for a Thematic Mapper Image. From one of the images to be used in the unsupervised classification.

2008						
Component	1	2	3	4	5	6
Eigenvalue	6412.9325	563.54866	473.20811	35.898131	15.31075	5.1573363
Percent Variance	85.44	7.51	6.30	0.48	0.20	0.07
2011						
Component	1	2	3	4	5	6
Eigenvalue	10036.029	989.18186	492.32301	167.04272	25.730342	16.715124
Percent Variance	85.58	8.44	4.20	1.42	0.22	0.14

These bands were combined with a calculated NDVI band derived from the red and near-infrared bands available in both images. This was done with the reasoning that NDVI values would provide some weight and definition to vegetation in the unsupervised classification process, while lessening the statistical emphasis on non-vegetative features such as impervious surface, water, and cloud cover. This emphasis on vegetation in the processing stage serves to reinforce vegetative areas of primary concern in this change analysis, which was used to determine if the study area had experienced extensive loss of foraging area (a potential factor effecting hive production). Both the calculation of NDVI values and the stacking of the images into one file were executed using "Index" and "Image Stack" functions, respectively. Using the combined images for each year, an unsupervised classification was done in IMAGINE 2011. The image was separated into 10 classes using 20 iterations of the process. The resulting images were then taken into ArcMap and reclassified using an ESRI-provided i-cubed 15 meter eSAT image layer as a reference layer. The ten classes of the image were identified as one of five classes: Water/Shadow, Cloud, Vegetative, Impervious Surface/Soil (Non-vegetative), and Mixed. The results of these classification schemes are shown in Figure 9.

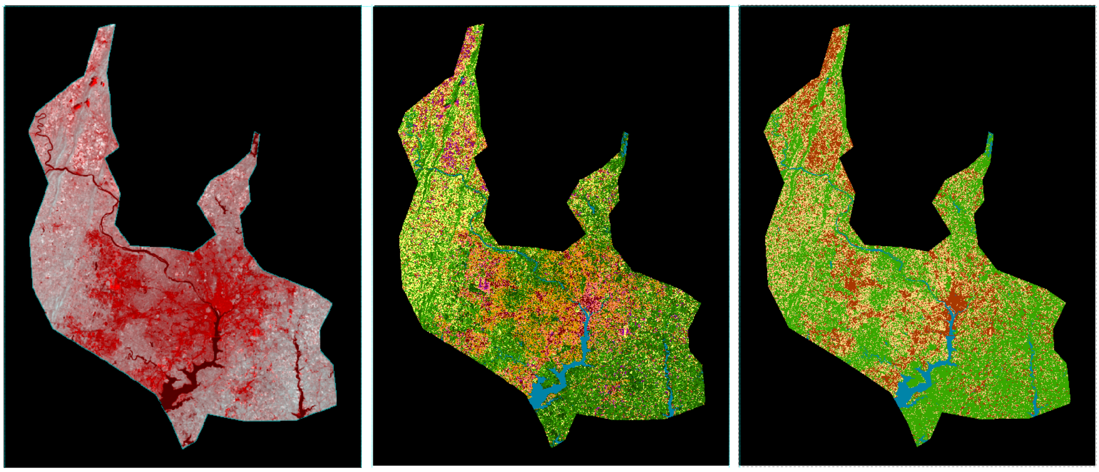

Figure 9. Three-step process for Classification of Thematic Mapper Images. From left to right: resulting principal component layer, 10-class unsupervised classification, simplification into four discrete classes. 2008 image.

These two ten-class images were then reclassified based upon the five descriptive classes listed above in order to simplify the resulting change analysis. This was done using the "Reclass" tool available in the ArcMap Spatial Analyst toolbar. The 2008 image exhibited no cloud cover whatsoever; the resulting reclassified image had four classes, whereas the 2011 image resulted in five classes after reclassification due to cloud cover. A portion of the 2011 image had been grouped within the "cloud cover" class when, based upon the reference layer, it was clearly otherwise (the Washington Dulles Airport, to be exact). This portion of the image was cropped and reclassified separately from the rest of the 2011 image. It was then merged back into the larger image by way of the "Mosaic to New Raster" function available in ArcMap.

The two final classified images were then used to create a change analysis raster using the ArcMap Spatial Analyst "Raster Calculator" function, adhering to a simple raster formula, using the numerical values assigned to each class as the variables.

*(2008 CLASS * 10)+2011 CLASS*

This formula resulted in the creation of a raster exhibiting values interpretable into a "From - To" form. Any raster value exhibiting a doubling of the same digit, for example, would mean that no change in identified land-cover type had occurred between the two images. A summary of all changes observed complete with frequency of changes in the image is collected in Table 3.

Table 3. Results of Thematic Mapper Change Analysis. Results that indicated no change in land-cover type are displayed in gray.

	From 2008 to 2011	Pixel Count	Pct.
0	Water to Water	256036	3.14%
1	Water to No Vegetationetation	12128	0.15%
2	Water to Part. Vegetationetation	961	0.01%
3	Water to Vegetation	1747	0.02%
4	Water to Cloud	444	0.01%
10	No Vegetation to Water	15677	0.19%
11	No Vegetation to No Vegetation	884711	10.86%
12	No Vegetation to Part. Vegetation	632387	7.77%
13	No Vegetation to Vegetation	42344	0.52%
14	No Vegetation to Cloud	25486	0.31%
20	Part. Vegetation to Water	15587	0.19%
21	Part. Vegetation to No Vegetation	314424	3.86%
22	Part. Vegetation to Part. Vegetation	1538793	18.89%
23	Part. Vegetation to Vegetation	322005	3.95%
24	Part. Vegetation to Cloud	13710	0.17%
30	Vegetation to Water	37309	0.46%
31	Vegetation to No Vegetation	233100	2.86%
32	Vegetation to Part. Vegetation	865803	10.63%
33	Vegetation to Vegetation	2907478	35.70%
34	Vegetation to Cloud	23860	0.29%

Change Summary	
No Change	68.60%
To No Vegetation	6.87%
To Partial Vegetation	18.41%
To Vegetation	4.50%
To Water	0.84%
To Cloud	0.78%

From this new layer it was determined that the study area exhibited less than 31% land cover type change over the 4 years examined; this change occurred primarily from vegetated and non-vegetated land covers to partially vegetated land cover (accounting for 18.40% of the 31% change). It is likely that these changes are due to nuances in the captured image between the two data sets themselves, rather than a significant change in land cover, as this middle category is a spectral "gray area" between the binary vegetation/no vegetation classes (likely vegetated urban and suburban areas). Cloud cover made up less than 1% of the 2011 image, and did not have a significant influence on the change analysis. From this low level of change exhibited over a four-year period it has been determined that use of a single Land-Use Land-Cover data set (NLCD 2006) is appropriate for defining areas of vegetation and impervious surface within the MODIS images for all study years.

Having determined the efficacy of NLCD data in determining vegetative areas for all years, the NLCD 2006 datasets within the study area were reclassified into a three-class scheme based upon their original NLCD classes' perceived level of vegetation (Table 4).

Table 4. NLCD Classes Categorized Based Upon their Reclassified Status.

No Vegetation		Partial Vegetation		Vegetation	
11	Open Water	21	Developed, Open Space	41	Deciduous Forest
23	Developed, Medium Density	22	Developed, Low Density	42	Evergreen Forest
24	Developed, High Density	81	Pasture/Hay	43	Mixed Forest
31	Barren Land	95	Emergent Herbaceous	52	Shrub/Scrub
				71	Grassland/Herbaceous
				82	Cultivated Crops
				90	Woody Wetlands

The resulting layers were mosaicked into a single reclassified layer describing the amount of expected vegetation in a given 30 square meter pixel based upon this NLCD reclassification. This dataset was then exported into a layer describing areas of partial and complete vegetation. This vegetation-positive layer was then used as a mask layer against MODIS imagery in the ArcMap Spatial Analyst "Extract by Mask" function, effectively removing any pixels in the MODIS imagery consisting of more than 50% non-vegetative area NLCD pixels. The resulting images exhibited MODIS-derived NDVI values clipped within 10 miles of a study-hive site, with areas of significant impervious surface removed (Figure 10). Impervious surface was removed because it exhibits little change between images, and would serve only to moderate the mean NDVI values of hive ranges. The removal allows for the observation of a greater range of NDVI values as they vary throughout the yearly vegetation cycle.

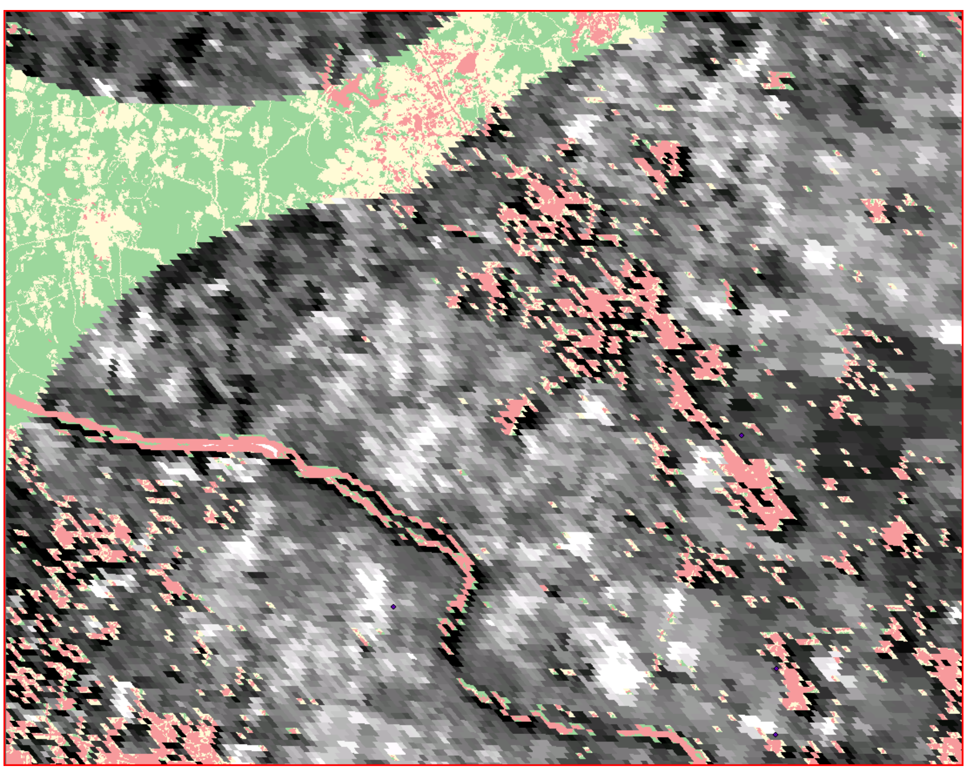

Figure 10. MOD13Q1 NDVI Product with Non-vegetative Areas Removed. Colored background is the reclassified vegetation/non-vegetation mask layer.

The resulting datasets, free of non-vegetative land-cover were then averaged over a four mile range from each HoneyBeeNet hive site, determined to be a point of diminishing returns for honey extraction (Beekman & Ratnieks, 2000). Due to limitations in ArcMap's "Zonal Statistics as Table" function (wherein any overlapping areas in a shapefile defining the zones results in an error) four separate shapefiles were created. These four shapefiles account for all sites without any overlapping ranges in a given file. These four files were used in a batch process with all images to determine the average NDVI value exhibited across each hive's four-mile forage range. The resulting tables were then merged by year to create an ongoing 16-day NDVI average for all sites. This yearly ongoing average was tabulated for the years 2008 - 2011.

The resulting product from this process was a series of 16-day NDVI observations at each established HoneyBeeNet site. In summary, this NDVI observation is the average 16-day NDVI values of all 250-meter pixels defined as vegetation within a four mile radius of the HoneyBeeNet site. A radius of four miles from each site was selected as both classic and contemporary literature consider this range to be a distance past which hives receive diminishing returns on effort (Eckert 1933, Beekman & Ratneiks, 2000). This generous estimate gives each hive an approximate foraging area of 50 square miles, with a few exceptions (of less area due to locations adjacent to large bodies of water).

Although the observation period of nectar flow varies from site to site within the HoneyBeeNet dataset, the NDVI values have been extracted for all sites over all the years in which imagery has been processed for this study (2008 – 2011). This was done for the sake of simplicity in processing; average NDVI values for which no nectar-flow data exists will be backed out prior to statistical analysis. When done in large quantities, having consistent data sets simplifies processing and reduces the likelihood of errors and omissions. Additionally, having all dates processed has done away with the possible need to go back and extract more NDVI values on different dates, a process further complicated by likely-irregular datasets at the time of statistical analysis. Having a full-years' worth of NDVI data may also provide some insight that NDVI data limited to HoneyBeeNet observation periods may not provide.

The 4 years from which NDVI values were extracted exhibit the typical seasonal variation expected of NDVI values in the Northern Hemisphere; with values reaching their lowest point in winter and peaking in the summer (Figure 11). Of particular note are the "drop out" values exhibited by some sites at the beginning and end of the year.

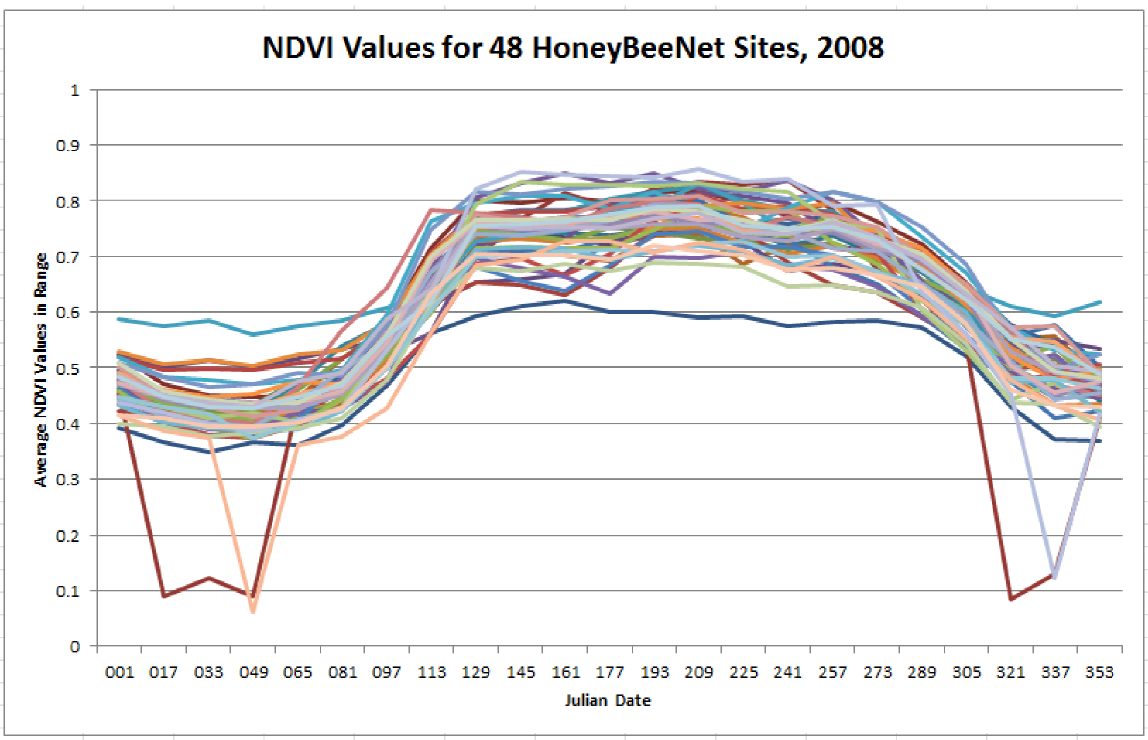

Figure 11. Extracted NDVI Values for All Sites in the Year 2008. Note seasonal variation and "dropped" values.

These dropped values were caused by snow events early or late in the year, which caused ground NDVI values to become extremely low due to the high albedo of snow cover. If one observes the whole of the data for the four year analysis, they exhibit extreme and widespread "drop outs" during what were major regional snow events.

Fortunately, few HoneyBeeNet hive sites reported observations over the whole of the year, and the focus of this study is upon impacts of vegetation variation during the foraging season, which occurs in the middle of the year for the mid-Atlantic region. Thus these large and significant dips in NDVI values were removed outright, having no effect on the study whatsoever.

Aside from these large seasonal dips, all sites exhibited the same seasonal oscillation, appearing as if they were in a large bundle. The only notable exception to this observation was the site run by the USDA. This site, manifesting as the dark blue line slightly below the "bundle" of sites, is located in the metropolitan DC area. A large amount of partially vegetated land cover has decreased the average NDVI of the site, but the site exhibited the same seasonal trends and many of the same variations within the oscillation that other sites exhibited. From this it is reasonable to conclude that the NDVI observations used in this study are an appropriate indicator of vegetative strength, as the values as a whole exhibit the same seasonal oscillation as vegetation in the Northern Hemisphere, and is consistent with observed values from literature. This can be considered a rejection of Sub-Hypothesis 1, as outlined earlier: H^0: *Within the design of the study, NDVI is not a reliable indicator of vegetative strength.*

Aggregation and Collation

To convert from overall hive mass to honey mass, each needed record available from the HoneyBeeNet website was downloaded in its original CSV format and collated into a single dataset based upon its Julian date. In addition, the HBN-provided QA code was added to this dataset in order to aid in determining each series' level of use to the study. As HoneyBeeNet data are reported as a daily change in overall hive mass, a conversion factor will be applied so that hive observation data are in the form of estimated daily change in honey mass.

A conversion factor was determined based upon McLellan's 1977 study. This study determined that by using the weight of a honeybee colony and the amount of time a colony has been harvesting nectar one can calculate the mass of honey within a colony to a great degree of accuracy.

$$H = -1416.0 + 0.7604C - 57.142D + 0.487D^2 + 0.00142CD$$

In which "H" represents the honey mass of a hive in grams, "C" the overall mass in grams, and "D" the number of days since the beginning of the nectar collection period.

HoneyBeeNet data are provided in a standardized format that reports changes in mass from the first day of observations in a given year without reporting the starting total weight of the hive. Thus it was necessary to estimate the starting weight of the hive to use as a baseline value for the changes that are recorded within each dataset. To do so, an estimated average hive weight at the beginning of a honey production period was used from Ambrose (1992) who states that a hive must be at a mass of approximately 30 pounds in early spring in order to survive in the time before nectar flows begin. Other sources place this value at 20 pounds (Morse, 1986). As hive-mass conversion was done at the beginning of the nectar collection period, an estimate of hive mass at 25 pounds was used for the beginning value, an average of the two most-quoted values in the literature. This value was used consistently across all hive records, as beekeepers typically make a fall harvest of all honey except for a small amount necessary for survival of the hive which would likely result in a mass in the range of 20-30 pounds at the beginning of the production season.

A honey production start date was required to determine the approximate honey mass of a hive. This was determined by examining all A-level HoneyBeeNet mass records for a given year. The start dates were identified as the first dates of the year in which any two reporting hives recorded a daily gain of one pound or greater and the sum gains of all reporting hives was positive. Although no existing methods were found regarding the prediction of honey production start dates for hives in aggregate, it was thought that these two indicators observed in tandem gave a good indication of the start of a season's positive nectar flow. Although determined by a metric heretofore unused, the resulting honey production-period start dates (Table 5) are consistent with the estimated start of the year available in literature (Ayers & Harmon, 1992).

Table 5. Calculated Honey Production Start Dates by Year.

Year	Calculated Start Date	First Observation Period
2008	April 1st (Julian 92)	April 22nd (Julian 113)
2009	April 5th (Julian 95)	April 21st (Julian 113)
2010	March 19th (Julian 78)	April 6th (Julian 97)
2011	April 7th (Julian 97)	April 21st (Julian 113)

As the MODIS-based NDVI data is only available in 16-day intervals, honey yield was aggregated into a 16-day measure by taking the sum of all losses and gains over the relevant 16-day period. That is, all losses and gains between Julian date "n-15" and "n" were summed, with "n" being the date upon which NDVI average data was released. This 16-day sum process was performed on all variables with daily records for the sake of consistency. An example of the 16-day Julian date periods used for each year in the study follows (Table 6).

Table 6. Example of 16-day Interval Observation Periods.

097	113	129	145	161...

Start dates for each year within the study are based upon the first available full set of 16 daily HoneyBeeNet mass observations for the honey production season. This makes the first 16 day observation set for all years in the study fall on Julian date 113, with the exception of 2010, an early season which started with Julian observation date 97.

Precipitation data were aggregated by sum in exactly the same manner for all precipitation-based metrics used in the study. Furthermore, a Year-to-Date precipitation sum for each 16-day period was calculated. Precipitation values of the previous aggregated observation in the series respective to the current date were also created (that is, a one-back or n-1 value of precipitation). This variable was created to account for any time-lagged correlation that previous precipitation might have with change in honey mass. It has been shown that periods of extreme precipitation can have a negative correlation with a colony's nectar collection, preventing bees from flying to collection sites (Holmes, 2002). Using precipitation data from this one-back perspective may circumvent the established negative correlations of current precipitation and nectar collection while allowing potential positive correlation between recent precipitation and honey gain to be established. Although some of these variables (such as precipitation: n-1, precipitation YTD, and NDVI change) were derived from date periods outside of the determined honey production period, great care was taken to ensure the data used to calculate these figures were complete before use in the analysis.

Changes in NDVI values were also included for analysis as an independent variable. This measure was a simple calculation of difference in NDVI between two 16-day observation periods. It is thought that this value will best approximate the rate of "green-up" an area is exhibiting.

In addition to independent variables that exhibited change over time, two temporally constant variables were used in the analysis. These variables do not serve to expose changes over time (as they remain constant on a per-site basis over the four year study period), but instead serve as an additional factor to consider when comparing differences in honey production between sites, regardless of the time of observation. The first of these constants is elevation, which is a value in feet above sea-level provided by the curators of the HoneyBeeNet data. It is considered to be accurate and sound; spot checks using a commonly available elevation dataset (USGS NED) confirm this to be true. The other constant value under consideration in this study is the percentage of land within each site's four mile radius that is classified as impervious. This NLCD-derived classification is identical to the classification scheme used to mask out non-vegetative values from the MOD13Q1 layer, as described above.

CHAPTER IV

RESULTS

Descriptive Results

Prior to advanced statistical analysis, each 16-day NDVI observation was collated into CSV format with the newly created 16-day aggregated observations of honey gain, precipitation, and YTD precipitation. Elevation, percentage of hive range covered by impervious surface, and NDVI change were also included. Critical statistics for several of the variables are outlined below in Table 7.

Table 7. Critical Statistics of Variables.

	Honey Gain (g)	NDVI	NDVI Change	Precipitation (mm)	Y-T-D Precip. (mm)	Impervious Surface
Mean	5136.00	0.735	0.022	515.30	4972.81	10.70%
Standard Dev.	8047.10	0.067	0.051	474.39	2916.88	11.49%
Maximum	61057.46	0.923	0.216	3895.00	17703.00	58.07%
Minimum	-6754.56	0.496	-0.132	0.00	219.00	0.04%
Median	2691.31	0.741	0.007	394.00	4629.00	7.34%

As can be seen above, the average honey gain experienced by a hive during the period used by this study was greater than 5 kilograms in a 16-day period. This generous growth rate, coupled with a standard deviation of 8 kilograms can be interpreted to mean that the observations in the study period captured both the highs and lows of honey production; this wide distribution of values should mean that having low representation of range in the independent variable will not be a statistical concern to this study.

The distribution of honey production values is right-skewed, with the peak of values in the range of 0 grams of gain to 1000 grams of gain, the tail leading off to higher values of gain. Only 72 of the 385 observation sets in the study have negative honey production values, which is a further encouraging trend in regards to the diversity of values in the independent. The histogram can be seen below in Figure 12.

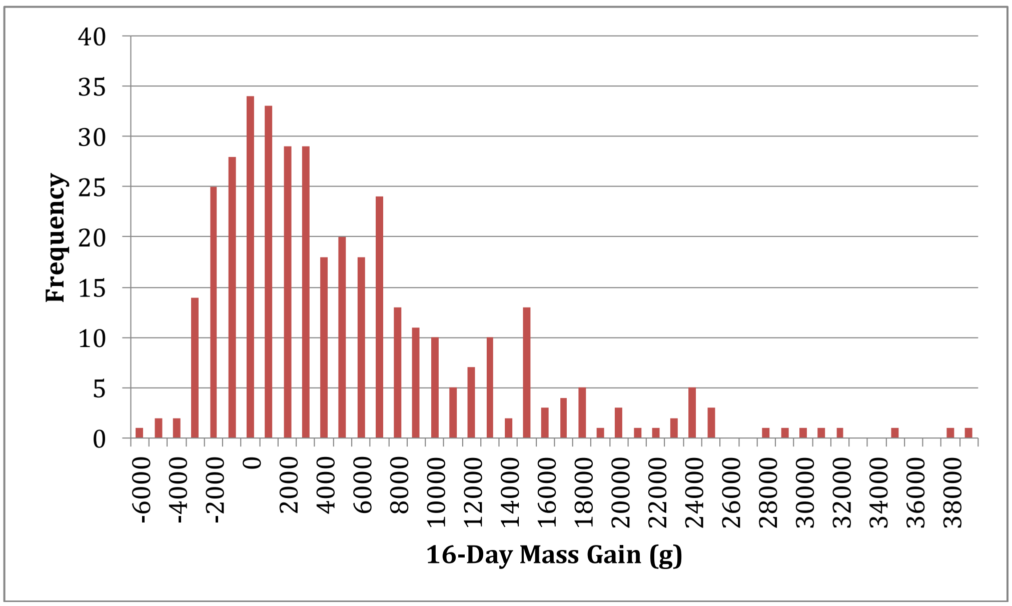

Figure 12. Histogram of Honey Production Values. One outlier value has been omitted from this histrogram.

Corresponding NDVI values are more compact but remain normal as well, with a left-skewed distribution centered about a peak value of 0.75. The average value of 0.73 is in fitting with the green-up scenario in a suburban and rural landscape that is the focus of this study. A histogram featuring all NDVI observations included in this study is shown below in Figure 13.

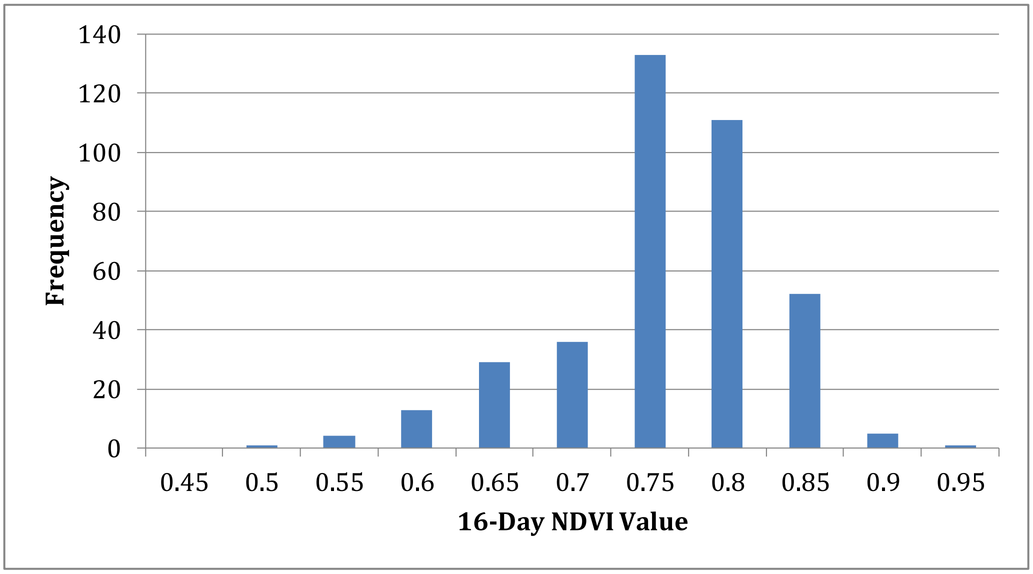

Figure 13. Histogram of NDVI Values.

To put these two figures together in an effort to establish a link between honey production and NDVI, all gain observations were sorted according to the NDVI conditions under which they were observed. This provides some descriptive statistics based upon the state of local vegetation at the time of honey gain observations (Table 8).

Table 8. Critical Statistics of Honey Mass Gains in Grams by NDVI Value.

NDVI Value	n	Mean Honey Gain (g)	Standard Dev. (g)	Median (g)
< 0.5	1	-608.98	-	-
≥ 0.5 < 0.6	17	5501.19	7242.55	3793.56
≥ 0.6 < 0.7	65	6138.97	7878.34	4141.14
≥ 0.7 < 0.8	244	4851.94	7326.47	2594.11
≥ 0.8 < 0.9	57	5065.23	10864.30	1623.53
≥ 0.9	1	12824.68	-	-

To inspect the possible trend of seasonality, individual hive records for each site were reviewed with the intent of finding the "honey production start date" for each site on any given year. This date was found by locating the earliest records in each hive's time series that exhibited two consecutive days in which hive mass gain was over one pound. One can be confident that such a steady gain is indicative that a hive's honey production, or at the least production capability, is well under way.

Using these start dates for each hive site, NDVI values were collected which represented the 16-day average before the production start date and the 16- day average after the production start date. The findings for 50 site-years are in Table 9 below.

Table 9. NDVI Values Related to Honey Production Start Dates.

Mean "Before" NDVI	0.628
Minimum "Before" NDVI	0.459
Median "Before" NDVI	0.634
Mean "After" NDVI	0.700
Maximum "After" NDVI	0.837
Median "After" NDVI	0.717
Lowest Change	-0.061
Average Change	0.072
Highest Change	0.188

Inferential Results

In order to test the null hypothesis that honey production is unrelated to NDVI and other factors, a linear correlation test was run between each independent variable and honey mass gain. Data were analyzed as a whole set and were parceled out into yearly sets, with resulting correlation factors as follows in Table 10. These factors quantify how much variance in honey production can be explained by the variance in independent variables listed in the leftmost column. Figures approaching zero indicate little relation between the two variances, and figures approaching one indicate a great amount of correlation between the two variables.

Table 10. R-squared Values for Various Independent Variables.

		Yearly Periods			
Correlation to HM (R^2)	All Years	2008	2009	2010	2011
NDVI	0.002	0.004	0.003	0.004	0.039
Precipitation	0.037	0.022	0.077	0.048	0.097
YTD Precipitation	0.0383	0.152	0.002	0.025	0.115
Precipitation, n-1	1.612E-06	0.004	0.002	0.042	2.699E-06
NDVI Change	0.004	0.046	0.008	0.004	0.029
Julian Date	0.131	0.309	0.059	0.118	0.187
n	385	65	94	131	95

To determine whether data within specific date-spans of the honey producing season show stronger relation to the independent factors in the study compared with other date spans (the existence of which would indicate a clear seasonality in an NDVI-honey production link), a moving-window analysis of 64-day periods over all years in the study was executed. The data were separated into groups of four 16-day observations and analyzed for correlation, as noted by Julian date below (Table 11). The results of this analysis support the null state of Sub-hypothesis 4: H^0: *An NDVI-honey production relationship does not differ over different periods of the year as studied in this thesis.*

Table 11. R-squared Values for Independents in Multiple Date Windows. Populations of each window denoted with "n".

	Moving Window Time Periods (Julian)						
Correlation to HM (R^2)	97-145	113-161	129-177	145-193	161-209	177-225	193-241
NDVI	0.069	0.025	0.003	0.014	0.020	0.038	0.048
Precipitation	0.090	0.104	0.086	0.029	0.043	0.027	0.008
YTD Precipitation	0.000	0.005	0.038	0.025	0.022	0.008	0.001
Precipitation, n-1	0.001	0.001	0.004	0.001	0.001	0.000	0.002
NDVI Change	0.197	0.106	0.020	0.004	0.007	0.002	0.006
Julian Date	0.174	0.053	0.092	0.214	0.164	0.085	0.149
n	136	177	188	185	176	166	154

In order to determine if a non-linear relationship exists between honey mass gain and the selected independent variables (for example, an exponential relation), logarithmic transformations were applied to relevant variables. As several of these variables (precipitation variables, NDVI change) had zero or negative values, translation values were added to all data within the variable to allow for logarithmic transformation. These translation values were calculated using the formula "$a=1-b^{min}$", where "a" represents the translation value and "b^{min}" represents the lowest value of a variable within the whole dataset. This, in effect, makes the lowest value in the range of a variable 1, with the rest of the values increasing from that point. This makes transformation of once-negative values into a logarithmic form possible. The "a" values for precipitation and its derivatives were one, and the "a" value used for honey mass gain was 6755.56. These translated values were then transformed using the common logarithm. Transformed independent variables were put into a linear regression scheme with an untransformed honey gain value, and a transformed honey gain value was compared against both untransformed and transformed independent variables. The results are below in Table 12 in the same R-squared format as the previous tables. All transformation configurations showed little correlation between the dependent and independents. Figure 14 features scatter plots for untransformed and log values of NDVI and honey production in all possible configurations.

Table 12. R-squared Values for Logarithmically Transformed Variables.

	Honey Gain (R^2)	log10 Honey Gain (R^2)
NDVI	-	0.006
Precip	-	0.018
YTD Precip	-	0.025
Precip, n-1	-	0.001
NDVI Change	-	0.000
Julian Date	-	0.132
log10 NDVI	0.002	0.006
log10 Precipitation	0.040	0.019
log10 YTD Precipitation	0.054	0.039
log10 Precipitation, n-1	0.001	0.001

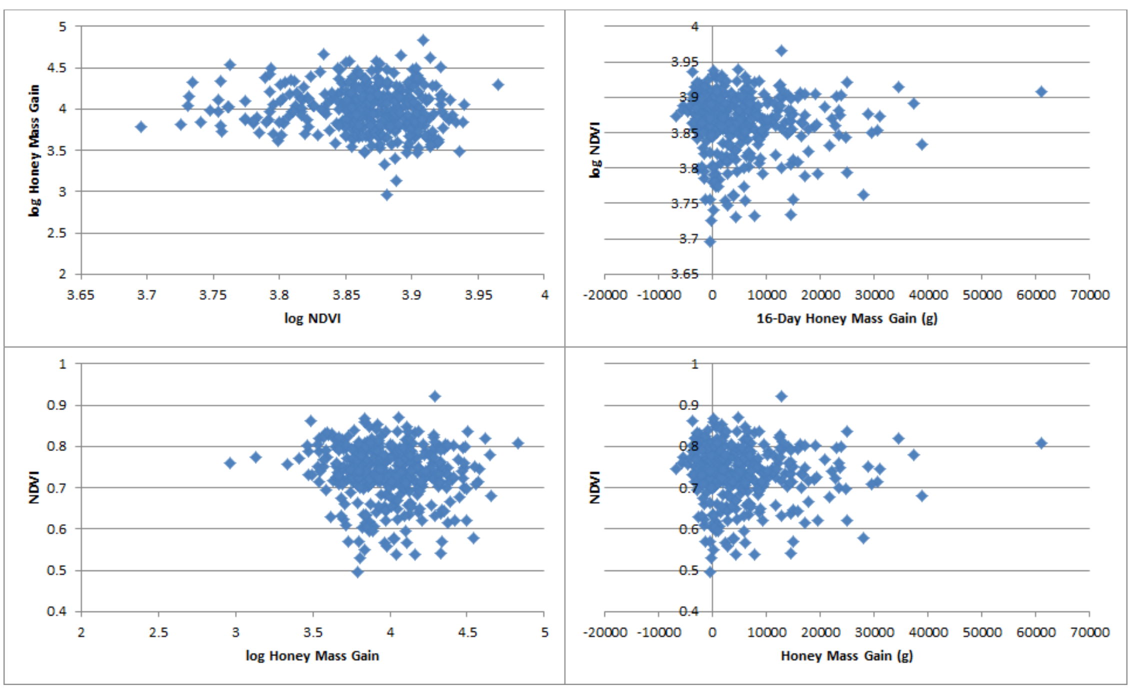

Figure 14. Scatter Plots of NDVI and Honey Yield Values.

As linear and other single-variable methods did not show promising results, little consideration was given to multivariate correlation schemes. A cursory application of the data into SAS's multivariate modeling capabilities resulted in nothing of note; all multivariate correlation models were too far below appreciable levels of fit and confidence to even be notable.

Additional analyses were run on so-called "temporal constants", that is, attributes of site locations that do not exhibit significant change over the study time. As discussed earlier, these two variables are the percentage of land cover classified as non-vegetative within a four mile radius of the hive and the elevation of the hive site. Average 16-day honey mass gain values for each site were calculated for all 4 years and for individual years within the analysis, as were total gains for each site in a year. Total honey mass gain figures were not calculated as a total of 4 years as some sites had no A-level data in certain years while others reported for all years, which would serve to distort reported four year totals for sites. The resulting coefficients of determination are as follows in Table 13.

Table 13. Coefficients of Determination for Temporal Constants.

	% Impervious	Elevation
All Years Average HMG	0.067	0.043
2008 Total HMG	0.288	0.470
2008 Average HMG	0.051	0.204
2009 Total HMG	0.120	0.003
2009 Average HMG	0.208	0.038
2010 Total HMG	0.033	0.055
2010 Average HMG	0.026	0.053
2011 Total HMG	0.303	0.268
2011 Average HMG	0.208	0.195

Also of note is an increase in NDVI from the "before production start" observation to the "after production start" observation. Only ten percent of the site-year NDVI values exhibited a decrease between the start-period observations, and of this 10 percent no observations showed a decrease in value greater than 6 hundredths. 60 percent of the observation sets showed an increase of greater than a tenth, a markedly large increase in vegetative robustness. An illustrated example of the gulfs between NDVI averages taken before and after a hive started honey production is shown below (Figure 15).

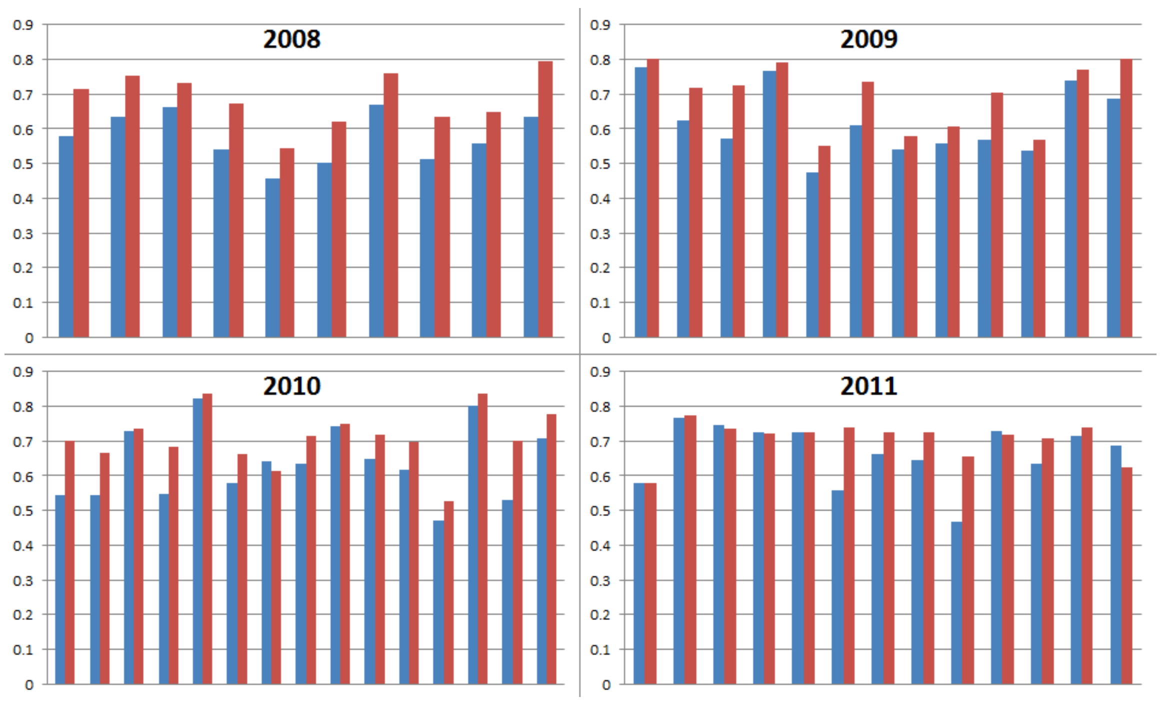

Figure 15. NDVI Values Before and After Honey Production Start Date. Organized by site-year. "Before production start" values are expressed in blue, "after production start" values are expressed in red.

CHAPTER V

DISCUSSION

Overview

Descriptive and inferential statistics were executed to answer this thesis's main inquiry if vegetation robustness (as indicated by NDVI values) is related to honey production within *Apis mellifera* colonies. The results showed very little correlation between honey production and the independent variables inspected in this study. Few statistics achieved a coefficient of determination above 0.1, with most results giving a level of confidence typically associated with random chance. Within the limitations of this study it is safe to conclude that honey production and the independent variables show no relation whatsoever. Thus, the basic null hypothesis that honey production has no relation to NDVI cannot be rejected. To answer the question more thoroughly, we must consider smaller portions of the hypothesis itself.

In the case of this study, was NDVI a good indicator of vegetative strength (as laid out in Sub-hypothesis 1)? Inspecting the results of the study, we see that NDVI exhibited a strong seasonal variation and an average range of 0.5022 (with a minimum average of 0.2945 and a maximum average of 0.7968) for all years, when snow related "drop-outs" have been removed. This range is a typical yearly range for a region with temperate vegetation like the Mid-Atlantic; accepting this we can conclude that, in the case of this study, NDVI was a valuable and accurate indicator of vegetative strength. However, other factors may have come into play in regards to the lack of correlation of NDVI data with honey production, especially the nuances in day-to-day variation in NDVI which would not be captured in an image product with 16-day temporal resolution. It has also been noted that NDVI exhibits shortcomings in dynamic range of images consisting of mostly vegetation (Huete, et al. 2002), that is, while NDVI may be esteemed for its ability to distinguish between high and low vegetation in a series of images, it may not be as suitable as other metrics (such as the Enhanced Vegetation Index) at detecting differences in images with large amounts of vegetation.

While NDVI has been deemed appropriate for the use of quantifying leafy green vegetation at a vast scale, another question presents itself in regards to the design of this study: was the use of NDVI proper for a study relating to honey production? Unfortunately, as outlined in the prior Literature Review, no peer-reviewed articles exist to establish precedent for the use of NDVI in a link to honey production. While NDVI has been used to determine the probable strength of a hive (Nightingale et al., 2008), it has never been used to link the production or yield of honey as this study has. Thus, it may be difficult to determine if NDVI was a useful tool within the purview of this study.

As for other factors such as precipitation and land use, the proof of their efficacy in predicting honey production has been established in the results. Sixteen-day rainfall totals, time-lagged 16-day rainfall totals, and year-to-date rainfall totals are shown to be uncorrelated to honey production within the temporal scale defined by the study (supporting the null-state of Sub-hypothesis 2: H^0*: There is no relation between any measure of precipitation and honey production in Apis mellifera colonies*). Similarly, elevation and land use (described earlier as "atemporal" variables) appear to have no relation to the amount of honey produced as an average or a sum over the study period (supporting the null-state of Sub-hypothesis 3: ***H^0: There is no relation between the amount of vegetated land-cover within an Apis mellifera colony's range and its honey production***). This lack of relation between land use type and honey production is a further confirmation of the Eckert's 1933 work, which stated that bees may travel up to four miles from the hive to collect nectar necessary for production, and that such a distance may not have flagging results on hive mass.

This thesis also seeks to address the potential of seasonality to effect the relation of independent variables to honey production. Results in regards to the 64-day moving-window analysis show little-to-no correlation between independents and honey production for any period under scrutiny. While a distinct seasonality to the correlation may still exist, it was not successfully established within the restraints of this study, considering that no correlation was found in either the basic analysis of all data or the moving-window analysis.

Additional Insights

What can one take away from the result that the null cannot be rejected? The easiest conclusion to make is that the null hypothesis is in fact true, that honey production does not, in reality, relate to any of the independent variables used in this study. It is not an unreasonable conclusion to come to, especially with the intensity of the variables encountered per the observations in this study; variables remained similar throughout the years observed, with no extreme or otherwise wildly different observations. The appearance of such variables might have shown a link between the variables observed and honey production when these extreme conditions present themselves, but such relations remain hypothetical.

The other possibility is that the study exhibits what is referred to as a Type II error; wherein the design of the study failed to determine the true nature of the relationship between honey production and vegetative strength, which could hypothetically still exist in some capacity. For example, the study may be at fault when considering factors of scale. While the outlook of this study was originally confident that imagery with a resolution of 250 meters would be sufficient for the scale of this study, literature regarding previous studies' use of MODIS imagery confirms that it is most useful for mapping at a "global, continental, or national scale" (Xie et al., 2008). Thus the nuances of vegetation around each hive site may have not been captured with such a course resolution product, and would explain the lack of relation between NDVI and honey production. The nature of the Type II error is speculative, as any oversights or faults in the study (by themselves or in combination) could cause such an error without much indication as to the offending element of the study. However, use of MODIS data with a regional-scale study seems to be one of the more likely causes of a hypothetical Type II error. One other likely cause of this hypothetical error is the aggregation of other daily measures (honey production, precipitation) to 16-day periods in order to match the 16-day average NDVI values reported by the MODIS dataset. This aggregation could have led to a loss in the fidelity of the daily data in which some nuanced relation could possibly exist.

Other Observations

Despite this, several distinct patterns between NDVI and honey mass gain can be discerned outside of the purview of inferential statistics; these descriptive patterns provide some insight into the nature of the seasonality of honey production and its broad-scope relation to NDVI.

Perhaps most notable is an observed seasonality in honey gain itself, as explored in Table 11. While the majority of observations used in the study (over 63 percent) coincide with a recorded 16-day NDVI average in the range of .7 to less than .8, these observations were low in regards to the average mass of honey gained under these NDVI conditions. In fact, if honey mass gains are separated into categories based upon the NDVI conditions they were observed to coincide with the largest average mass gains by far (with the exception of a single outlier in the NDVI range of .9 and above) fall within the NDVI range of 0.6 to 0.7. The average honey gain under these NDVI conditions outweighs all other average recorded gains by over one kilogram.

Whether this indicates a "sweet spot" for honey gain as it relates to NDVI or is merely a seasonality factor that happens to coincide with NDVI values of this range is open to interpretation. Three NDVI ranges of 0.1 values (0.5x, 0.6x, and 0.7x) share approximately similar standard deviations of honey production above seven kilograms. Further revealing are start dates (the point at which the mass production of a hive begins to outweigh its mass consumption), as laid out in Table 9. These dates typically occur before full green-up in a region (full vegetative strength corresponding to NDVI values in the 0.7 to 0.8 range), with an average NDVI value of approximately 0.62. As many of these sites began their observations early in the year where days of continual small mass losses (typical of winter) were observed before a spike of gains, it may be that these lower NDVI values represent a lower bound below which no significant hive mass gain occurred. The 2010 season, which started honey production over two weeks earlier than all other years in the study, exhibited the same patterns in regards to concurrent NDVI values despite beginning production ten or more days earlier than in other site-years, as can be observed in Table 9.

Regardless of these observations, this study still cannot make any statistically concrete statements about the nature of honey production as it relates to observed vegetation abundance or strength.

Future Developments

While the failure to dismiss the null hypothesis is result enough for insight, the result of this study emphasizes the merit of future elements that may be incorporated into a study of honey production as it relates to satellite imagery. Foremost is the use of alternative methods of quantifying vegetative robustness. While MODIS imagery may still be a useful tool for quantifying vegetation over a large swath of land, better results may come from using a different vegetation index such as EVI (the "Enhanced Vegetation Index"), which in some studies has shown to be a more effective indicator of vegetative strength when vegetated areas predominated the analyzed image (Huete, et al., 2002).

Alternatively, another sensor product could be used in lieu of MODIS imagery. While LANDSAT data is known for its easy access and higher spatial resolution (at 30 meters per pixel rather than MODIS's 250 meters), it, as mentioned, often has cloud cover featured prominently within its snapshot images. ASTER, which is aboard the same Terra craft as MODIS, suffers the same problem of intermittent cloud cover. Naturally, flaws in the time-of-capture images of these products are the drawback to these more high-resolution products. A successful follow-up study might make use of more reliable high-resolution products requiring significant processing (such as image fusion) or make use of a larger honey production dataset over which less-reliable imagery products (LANDSAT, ASTER) can be applied (Xie et al., 2008). An excellent option for future work on this topic (remaining true to most methods established within the work already done) would be to wait for the release of more HoneyBeeNet data for upcoming years, using this larger spread of honey production values to make up for the loss of some dates found in the higher resolution ASTER image product. The end result would be a similar number of observation pairings when compared to the current study resources (with a 16-day return period and some dropped observation days), as well as an increased spatial resolution, and a one-to-one link between daily honey production and a daily ASTER observation (rather than the MODIS 16-day aggregated production measure used).

Another possible venue of advancement is the use of locally derived metrics of vegetative health such as a vegetative survey or ground-level observation. This approach would ensure that data were recorded locally and daily; the creation of daily data would ensure that daily hive mass observations could be used without aggregation, allowing a (hopefully) more accurate representation of the day-to-day changes in honey production possibly brought about by fluctuations in vegetative health. This vegetative survey might manifest as a written observation of the presentation of various selected species (especially those relevant to honey production in the area), which could then be classified into one of several descriptive categories for the purpose of statistical analysis. Another more quantitative approach might make use of ground-based vegetative photography of identical frame over multiple days, enabling quantitative analysis of the image series.

Possibly the most interesting approach to solving issues with data frequency and fidelity would be the use of an Unmanned Aerial Vehicle (UAV) to capture vegetation data. These platforms have been proven to be cost-effective and can be flown with remarkable frequency (daily, weather permitting) and are not subject to the same restrictions as an orbital remote-sensing platform, such as interference from higher-altitude cloud-cover or a long period between area fly-overs. The efficacy of UAV-based imagery has been proven in the realm of vegetation monitoring, so long as care is taken in the calibration of the sensors and products (Berni, et al. 2009). The use of UAVs to produce daily image products would prove especially useful during the green-up period described earlier in this thesis. Day-to-day changes in different plant species that may rapidly gain vegetation would be more easily detected and some relationship between the phrenology of certain nectar-bearing plants and honey production may come to the fore as a result of this finer imagery.

One final consideration for future development in the line of this thesis: a more focused look at health indicators of hives used in the study. While the HoneyBeeNet data used in this study has undergone quality assessment procedures, these QA guidelines are primarily based upon changes in mass in a hive. It may be that certain hives underperformed due to health issues such as disease or parasite infestation that curbed a hive's growth but failed to reduce its production to a level detected by the QA process. In addition to weight data it may be advantageous for those collecting field observations of hives to take note of any observed minor health issues in hives, for the sake of complete disclosure. This data may be integrated in the QA process or even within the analysis of any future studies using HoneyBeeNet data, and the use of which would ensure a more complete data product and more reliable results from studies using the data. Naturally this would require more time and dedication (in the form of opening the hive to check frequently) from those who volunteer their hive mass data without any compensation; such a requirement for the data should perhaps not be required but encouraged when possible.

CHAPTER VI

CONCLUSIONS

In this thesis I attempted to reject the null hypothesis that honey production in *Apis mellifera* colonies is not linked to vegetation strength as measured by NDVI from remote sensing products. Hive mass observations of managed European honeybee hives in the Mid-Atlantic region, as provided viaHoneyBeeNet, were compared alongside NDVI values from the MODIS sensor. These image products were modified to focus only upon partially and fully vegetated areas; additional factors such as rainfall and land-cover type were taken into statistical consideration.

NDVI was found to have no relation to honey production in the hives observed. Across all statistical metrics, no relation was found between honey production and any independent variable (NDVI, NDVI change, rainfall, year-to-date rainfall, elevation, or area of vegetation within hive range). Despite a this, a few patterns regarding honey production in hives and its apparent relation to NDVI (without any statistical rigor) can be made: honey production values are the highest in the median observed ranges of NDVI values encountered in the study and NDVI almost invariably was on a marked increase when hives began to gain honey mass (or "break even").

With this result one must accept that honey production may not be strongly linked to NDVI values or any other indicators inspected in this study. Whether this result was a reflection of the true nature of the relationship (or lack thereof) between the two subjects or was arrived at through a flaw of study design was not determined. If a study is to be continued in a manner similar to this thesis, it is recommended that a different, higher resolution image product be collected and additional hive mass observations collected in order to compensate for the loss of some days due to flaws in certain images that come with higher-resolution products.

Vegetative strength, precipitation, and land use; at the outset of this study, it was thought that these factors would show some amount of influence upon the honey production within a hive; that these independent variables, as they varied through both space and time, would similarly influence change in honey productions of hives assumed to be similar.

The assumption that all hives used within the HoneyBeeNet were approximately similar in size and strength may have ultimately distorted the results as well. This was true in regards to certain factors: hives were considered to be in good health (as they had survived through the winter), free of significant losses due to robbing and disease, and were managed by apiculturists. However, being a community of animals whose behaviors are not yet fully understood, bees and beehives remain a somewhat unpredictable entity whose operations and whims adhere to only the broadest of developed theories and formulas (for example, Steffan-Dewenter & Kuhn, 2002).

The realities at play in this study then most likely fall somewhere in the middle of these two conceptual models; while hives were monitored and maintained to be as homogeneous as possible (the resulting data put under quality assessment as well), hives still exhibit variation in both their general natures and responses to outside variables. Granted, these variations were not accounted for in this study.

It is entirely possible that little correlation exists between NDVI values and honey yield; certainly honey bees need nectar and pollen supplies to survive and produce honey, but it may be that the strength of vegetation in regards to the abundance of these natural resources for bees is a non-issue in all but the most extreme cases. Preexisting literature may bolster this claim. In a 2002 study, Holmes found that honey yields in the British Isles were largely dependent upon weather patterns and overall climate when inspected over several decades (accounting for approximately 80 percent of the variation within honey yields). Another source finds that honey yield increases as hives are located closer to thick, vibrant vegetation (Sande, 2009). However, this study attributes the increase to increased biodiversity and nectar sources that bloom throughout the whole of the year, not increased robustness of existing vegetation. If both of these studies shed some light upon the mechanisms that drive honey production, NDVI may have little correlation with honey production, except in cases of extreme drought or areas with limited-to-no vegetation.

Alternatively, the study design could have also contributed to the failure to disprove the null hypothesis. To reiterate the example of extreme cases of vegetation scarcity, it is entirely possible that the limited study area did not show nearly enough variation in its NDVI range for any correlation to be found. While the area exhibited change in its NDVI over time, the range of NDVI values during a given period of time was small. Additionally, there is a large range of foraging options for hives within a 50 square mile area; vegetation populations could fail and bees could still get the needed resources for appreciable honey production except in the most extreme of cases. After all, bees have been found to travel up to four miles from the hive across barren terrain to reach needed resources (Eckert, 1933), and the mid-Atlantic region, especially with its suburban landscape, is known to be full of proper forage for bees (Waddington, 1994), in addition to its locally native vegetation.

The final conclusion one can make is thus: under the design and limitations of this study, NDVI and other metrics such as precipitation cannot be easily linked to honey production within a hive in the short-term. This may be due to the design and focus of the study, or the very nature of bees themselves. In hindsight the focus of this study is nearly presumptuous given what is already known about bees. It should have been expected that honey bees would seek out any available resources despite local scarcities, as millions of years of evolution (Danforth et al., 2006) have doubtless given them ample time to adapt to varying states of vegetative abundance. The resourcefulness and work ethic of bees has been noted and valued by humans since antiquity; this study, despite its lack of findings, may serve to highlight the complexity and unpredictability of *Apis mellifera*'s interaction and use of its surrounding environment.

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