The Great Bee Migration: Supply Analysis of Honey Bee Colony Shipments into California for Almond Pollination Services

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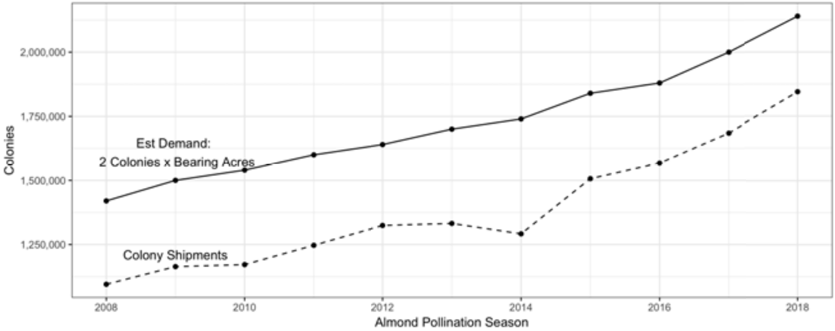
Almond Pollination Services

- California supplies 82% of world almond production
  - Approximately 1.1 million acres in 2018
- 2018 almond bloom required ≈ 81% of U.S. honey-producing colonies
  - All other spring blooming crops in U.S. use roughly 30% of almond pollination colonies
- Almond pollination fees have increased by 11% in real terms since 2007
  - CSBA average per-colony fee in 2018: $184
  - UCCE estimates 20% of annual operating costs for almond production (Duncan et al., 2016)

Almond Pollination Services

Colony Shipments into California and Estimated Demand for Almond Pollination Services, Seasons 2008-2018



Sources: Apiary Shipments through California Border Protection Stations, CDFA Plant Health and Pest Prevention Services; USDA NASS 2008-2016 Almond Acreage Reports

Research Objectives

Explore characteristics of the supply of almond pollination services:

- From which states are colonies transported?
- What are price elasticities of supply for honey bee colony shipments?
- How has the supply source changed as almond acreage has increased in recent years?
  - Where will colonies come from to meet future demand?

U.S. Beekeeping Industry

- Regional variation exists in beekeeping due to forage sources and weather (Nye, 1980)
  - 88% U.S. colonies owned by commercial operations with 300+ colonies (Daberkow et al., 2009)
  - Most commercial beekeeping operations are migratory (Bond et al., 2014)



Supply of Almond Pollination Services

- Available supply depends on current populations of honey bee colonies in U.S.
  - Marginal costs increase with increases in distance from California
  - Opportunity costs exist in some areas with honey production during almond bloom
- Beekeeping operations not willing to expand at current almond pollination fees
  - Forage is a limiting factor for honey bee populations (Champetier et al., 2015)
  - Expanding a beekeeping operation's capacity involves large fixed investments
    - Must expand by the truckload $\approx$ 400 colonies

Round-Trip Transportation Costs

Region	Average Distance One-way(Miles)	Minimum ($/Colony)	Average ($/Colony)	Maximum ($/Colony)
Pacific Northwest	781	9.62	11.71	13.81
Mountainous	896	6.30	13.44	18.32
Southwest	1,049	10.08	15.73	22.12
Plains	1,560	22.17	23.41	25.55
North Central	2,125	27.73	31.88	36.27
Southeast	2,349	26.85	35.23	41.85
Northeast	2,960	40.68	44.40	49.16

† Average Distance calculated from averaging the distance from the centroid of each state to Madera, CA. Per-Colony Shipment Costs calculated using a per-mile shipment cost of $3, and 400 colonies per truck shipment from the centroid of each state to Madera, CA.

Demand for Almond Pollination Services

- Industry rule of thumb: 2 Colonies/Acre Almonds
- Inelastic demand
  - Not influenced by crop or pollination prices (Rucker et al. 2012)
  - Not influenced by colony strength (Goodrich, 2017)

Almond Pollination Services Market Equilibrium

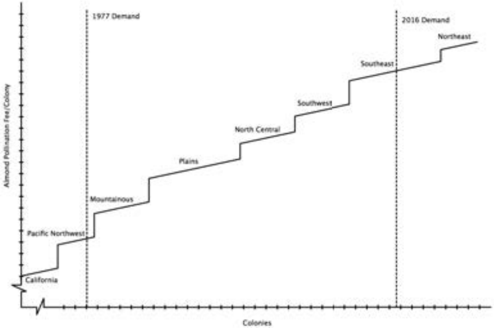
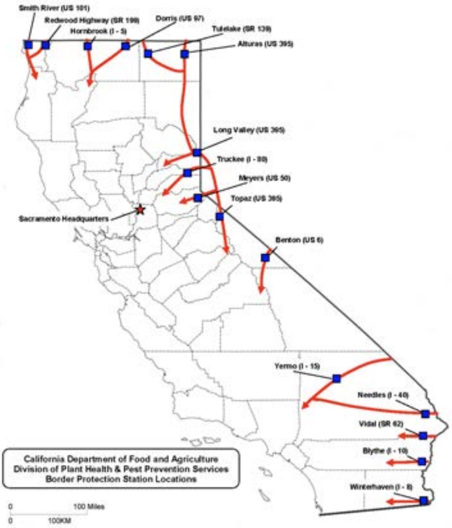


Table 2: U.S. Regional Honey Bee Colony Populations, 1978 and 2015

Region	December 31, 1978 Colonies	December 31, 1978 Percentage of U.S.	Maximum Oct-Dec 2015† Colonies	Maximum Oct-Dec 2015† Percentage of U.S.
Plains	403,838	15.81%	571,500	19.88%
Mountainous	309,174	12.10%	345,000	12.00%
Pacific Northwest	130,589	5.11%	203,000	7.06%
Southwest	166,021	6.50%	295,000	10.26%
Southeast	465,389	18.22%	603,000	20.98%
North Central	483,772	18.94%	319,000	11.10%
Northeast	111,290	4.36%	95,400	3.32%
California	477,013	18.67%	750,000†	26.09%
Total U.S.	2,554,390		2,874,760	

Apiary Shipment Data

- Individual truck shipments into California's 16 Border Protection Stations (BPS)
  - CDFA inspects to prevent spread of invasive species
- Information collected:
  - Origin state
  - Destination in California
  - Number of honey bee colonies
- April 1, 2007-November 28, 2018



Summary Statistics

	N	Mean	St. Dev.	Min	Max
Shipments	341	102.00	153.66	0.00	769.00
Colonies Shipped	341	40,629.11	61,712.58	0.00	329,432.00
Net Shipment Price	341	51,951.03	5,174.84	41,703.93	64,233.19
Net Per-Colony Price	341	129.88	12.94	104.26	160.58
Max Honey Producing Colonies	341	66,973.61	94,299.88	4,000.00	510,000.00
Winter Mortality Rate	341	0.31	0.13	0.06	0.73
Diesel (Avg $/gal Oct-Feb)	11	3.19	0.58	2.28	4.02

$$NetShipPrice_{it} = \left(AlmondPollFee(\$/Col)_t \times \frac{400\ Col}{Shipment}\right) - (2 \times MiFromMadera_i \times \$3/mile)$$

$$NetPerColPrice_{it} = AlmondPollFee(\$/Col)_t - \left(2 \times MiFromMadera_i \times \$3/mile \div \frac{400\ Col}{Shipment}\right)$$

Data Sources:

Apiary Shipments through California Border Protection Stations, CDFA;

CSBA Pollination Fee Surveys 2008-2018;

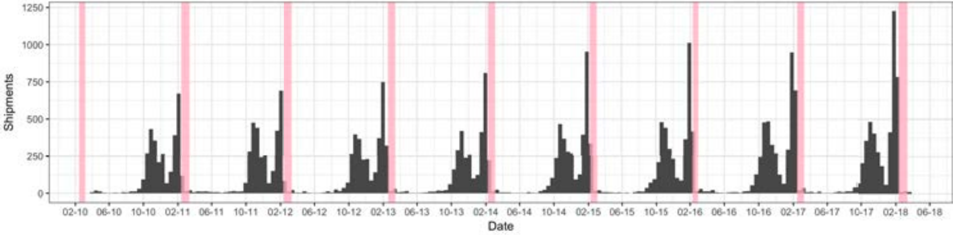
USDA Honey Report 2007-2017;

BIP Colony Loss Surveys 2007-2008 through 2017-2018;

EIA Gasoline and Diesel Fuel Update October 2007-February 2018

Histogram of Colony Shipments into California

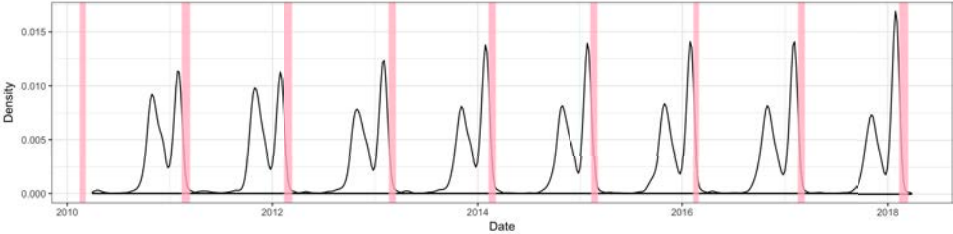
Bi-Weekly, March 2010- April 2018 *(Almond Bloom Period Highlighted)*



Sources: Apiary Shipments through California Border Protection Stations, CDFA Plant Health and Pest Prevention Services; Blue Diamond Grower's Crop Progress Reports

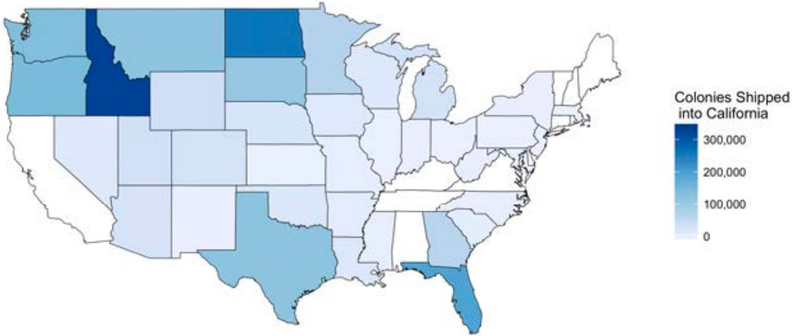
Density of Colony Shipments by Almond Pollination Season

Seasons 2011-2018 *(Almond Bloom Period Highlighted)*[†]



[†]Densities are calculated for each almond pollination season which we define as April 1 of the previous year through March 31 of the almond pollination season year.
Sources: Apiary Shipments through California Border Protection Stations, CDFA Plant Health and Pest Prevention Services; Blue Diamond Grower's Crop Progress Reports

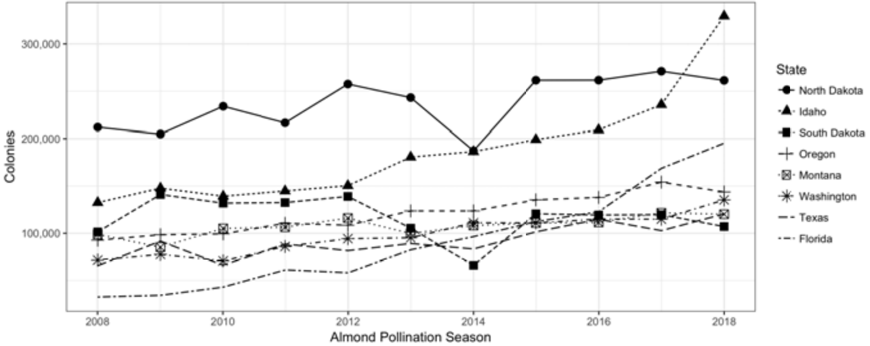
2018 Colony Shipments by State



Source: Apiary Shipments through California Border Protection Stations, CDFA Plant Health and Pest Prevention Services

2008-2018 State Shipments

Colony Shipments into California from Eight States with Largest Number of Colonies Shipped in 2018



Source: Apiary Shipments through California Border Protection Stations, CDFA Plant Health and Pest Prevention Services

Geographically Weighted Regression

- Geographically weighted regression (GWR) accounts for spatial heterogeneity and estimates geographically varying coefficients
- GWR Model (Brundson et al., 1998):

$$Y_{it} = \beta_0(x_i, y_i) + \sum_k \beta_k(x_i, y_i) X_{it} + \mu_{it}$$

- where
  - Y_{it}: dependent variable
  - X_{it} : matrix of explanatory variables
  - x_i and y_i: geographic coordinates
  - μ_{it}: error term.

GWR Coefficients

- Coefficient estimates

$$\hat{\beta}(x_i, y_i) = (X'W(x_i, y_i)X)^{-1}X'W(x_i, y_i)Y_{it}$$

- where $W(x_i, y_i)$ is a distance based weighting matrix.

- Gaussian weighting matrix: $w_i = \exp[-\frac{1}{2}\frac{d(x_i,y_i)}{h}]^2$
  - $d(x_i, y_i)$: Euclidean Distance
  - h: bandwidth chosen through a cross-validation process (Fotheringham et al., 2003)

GWR Models

- Model 1 based on apiary truck shipments from state i for almond pollination season t:

$$Shipment_{it} = \beta_0(x_i, y_i), + \beta_1(x_i, y_i) NetShipPrice_{it} + \beta_2(x_i, y_i) HPCol_{it-1} + \beta_3(x_i, y_i) WM_{it} + \beta_4(x_i, y_i) Diesel_t + \mu_{it}$$

- Model 2 based on colonies shipped from state i for almond pollination season t:

$$ColShipped_{it} = \beta_0(x_i, y_i), + \beta_1(x_i, y_i) NetPerColPrice_{it} + \beta_2(x_i, y_i) HPCol_{it-1} + \beta_3(x_i, y_i) WM_{it} + \beta_4(x_i, y_i) Diesel_t + \mu_{it}$$

- x_i and y_i: the longitude and latitude values of the centroid of state i

OLS Estimates

	Dependent variable:	
	Shipments (1)	Colonies Shipped (2)
Net Shipment Price	0.01***	
	(0.001)	
Net Per-Colony Price		1,413.87***
		(144.48)
Max Honey Producing Colonies	0.001***	0.50***
	(0.0000)	(0.02)
Winter Mortality Rate	−96.0***	−35,674***
	(35.43)	(13,508.10)
Diesel (Avg $/gal Oct-Feb)	15.4*	4,996
	(8.52)	(3,247.95)
Constant	−512.1***	−181,218***
	(69.10)	(26,344.55)
Observations	341	341
R^2	0.72	0.75
Adjusted R^2	0.72	0.74
F Statistic (df = 4; 336)	215.0***	247.8***
Note:		*p<0.1; **p<0.05; ***p<0.01

GWR Model 2 (Colonies Shipped) Estimates

	Min	1st Quartile	Median	3rd Quartile	Max	Global
Intercept	-617, 868.80	-22, 101.78	-5, 182.71	686.59	304, 933.30	-181, 218.40
Net Per-Colony Price	-1, 610.54	-14.98	49.55	204.94	4, 701.29	1, 413.87
Diesel (Avg $/gal Oct-Feb)	-23, 364.93	-539.59	-133.84	216.69	13, 667.94	4, 996.45
Max Honey Producing Colonies	0.01	0.25	0.41	0.53	2.02	0.50
Winter Mortality Rate	-174, 662.70	-4, 897.29	-1, 724.50	680.78	11, 337.49	-35, 674.37

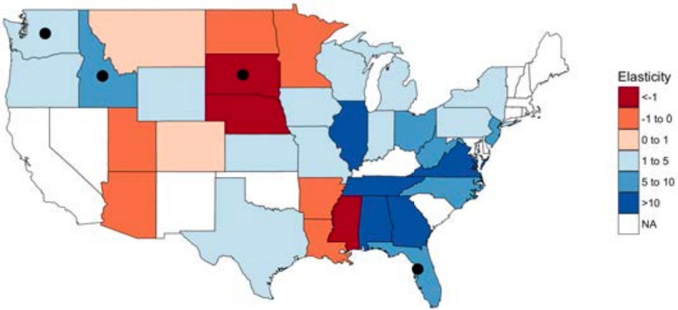
Brunsdon, Fotheringham and Charlton (2002) ANOVA

SS OLS residuals (in 1000s)	SS GWR residuals (in 1000s)
327,846,935	36,392,891

$F = 9.01$, $df1 = 336.0$, $df2 = 226.5$, p-value < 0.000

Note: Global is equivalent to OLS

Supply Elasticity Estimates for Colonies Shipped



● denotes statistical significance at the 90% level using a Bonferroni adjustment for multiple hypothesis tests

†Elasticities were calculated using 2008 prices and quantities

Negative Supply Elasticities?

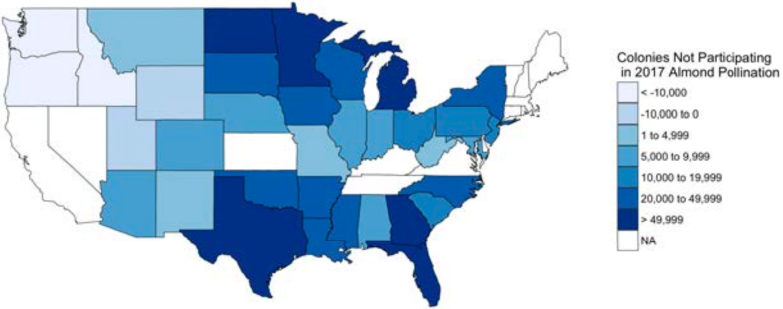
Pacific Northwest Colony Shipments for the 2017 Almond Bloom

			Number of Colonies		
State	Shipments	Colonies Shipped	July 1, 2016	October 1, 2016	January 1, 2017
Idaho	560	235,695	79,000	121,000	95,000
Oregon	485	154,161	107,000	98,000	71,000
Washington	341	114,892	57,000	65,000	68,000

Future Demand for Almond Pollination Services

- Roughly 148,000 additional colonies required by 2020
  - 2 colonies/acre x 64,406 bearing acres of traditional varieties
  - 1 colony/acre x 19,519 bearing acres of self-fertile
- To get those additional colonies, almond pollination fees would have to increase by:
  - OLS estimates: 1.6%
  - GWR spatial estimates: 7.9%
- Where will these colonies come from?

State Estimates of Available Colonies for 2017 Almond Pollination



†NAs exist for Delaware, Nevada, New Hampshire, and Rhode Island because USDA does not publish honey bee populations for these states. State estimates do not factor in winter mortality rates.

Sources: Apiary Shipments through California Border Protection Stations, CDFA Plant Health and Pest Prevention Services; USDA Honey Bee Colonies Report May 2017

Summary and Implications

- Spatial variation important in honey bee colony shipments into California for almond pollination
  - Beekeepers in eastern U.S. have relatively high supply elasticities
  - Negative supply elasticities in some states imply shift to transship colonies through Pacific Northwest States
- Spatial estimates suggest almond pollination fees will have to increase to an average of $200/colony by 2020
  - Likely states: Florida, Georgia, Texas
  - Fee increase depends on extent of opportunity costs from honey production during bloom

Thank you!

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Model 1 GWR Estimates

	Min	1st Quartile	Median	3rd Quartile	Max	Global
Intercept	-1,278.01	-67.93	-27.34	-3.82	729.34	-512.08
Net Shipment Price	-0.01	-0.00	0.00	0.00	0.03	0.01
Diesel (Avg $/gal Oct-Feb)	-61.80	-1.36	-0.46	1.21	30.17	15.35
Max Honey Producing Colonies	0.000	0.001	0.001	0.001	0.005	0.001
Winter Mortality Rate	-356.82	-13.10	-4.47	2.17	36.62	-95.97

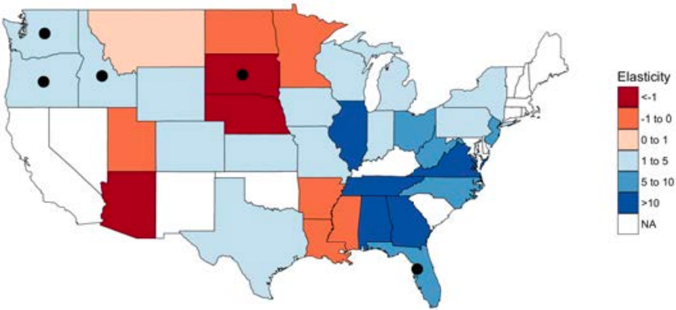
Brunsdon, Fotheringham and Charlton (2002) ANOVA

SS OLS residuals (in 1000s)	SS GWR residuals (in 1000s)
2,255.51	208.16

F = 10.84, df1 = 336.0, df2 = 229.3, p-value < 0.000

Note: Global is equivalent to OLS

Supply Elasticity Estimates for Truck Shipments



• denotes statistical significance at the 90% level using a Bonferroni adjustment for multiple hypothesis tests

† Elasticities were calculated using 2008 prices and quantities

GWR Model 1 Coefficient Tests

	F statistic (1000s)	Numerator d.f.	Denominator d.f.
(Intercept)	10,155***	58.56	244.27
Net Shipment Price	17,757***	82.41	244.27
Diesel (Avg $/gal Oct-Feb)	2,270***	78.80	244.27
Max Honey Producing Colonies	482,655***	37.47	244.27
Winter Mortality Rate	3,644***	34.41	244.27

Null Hypothesis: All GWR coefficients equal — *p<0.1; **p<0.05; ***p<0.01

GWR Model 2 Coefficient Tests

	F statistic (1000s)	Numerator d.f.	Denominator d.f.
(Intercept)	9,602***	58.58	240.79
Net Per-Colony Price	15,304***	82.43	240.79
Diesel (Avg $/gal Oct-Feb)	1,946***	78.83	240.79
Max Honey Producing Colonies	520,505,940***	37.47	240.79
Winter Mortality Rate	3,675***	34.41	240.79

Null Hypothesis: All GWR coefficients equal   *p<0.1; **p<0.05; ***p<0.01