Supplemental materials for:

Title: Disease ontogeny overshadows effects of climate and species interactions on population dynamics in a nonnative forest disease complex

Authors: Garnas, J. R., Houston, D.R., Ayres, M. P. And C. Evans

File contains: Tables A1-A5

Figures A1-A5

Supplemental literature cited

SUPPLMENTAL TABLES

Table A1. Geographic locations and sampling details for 28 sites monitored for beech bark disease severity, approximately yearly. Sites were sampled approximately yearly between 1979 and 1992.

Site #	Latitude	Longitude	State	County	Year of scale insect colonization	Elevation (meters)	Sampling range	Count of trees	Years sampled
102	44.8253	-68.5930	ME	Penobscot	1935	69	1979-92	105	13
103	44.8186	-68.5788	“	Penobscot	1935	50	1979-92	51	13
104	44.8211	-68.5872	“	Penobscot	1935	50	1979-84	213	6
301	43.7168	-72.5930	VT	Windsor	1945	535	1983-91	60	9
302	43.4154	-72.7353	“	Chittenden	1960	710	1983-91	50	9
303	42.8382	-73.0910	“	Bennington	1945	600	1983-91	50	9
440	42.2927	-73.1425	MA	Berkshire	1945	663	1983-92	200	9
441	42.6941	-72.9866	“	Berkshire	1945	625	1983-92	200	9
501	41.9649	-72.9936	CT	Hartford	1945	300	1979-92	139	12
509	42.0343	-72.9677	“	Hartford	1945	417	1979-92	200	13
610	43.6333	-75.3333	NY	Lewis	1960	350	1979-92	266	13
611	43.4144	-75.3696	“	Oneida	1960	355	1979-92	203	13
612	44.2495	-74.3459	“	Essex	1960	530	1979-92	198	13
613	44.4971	-74.0272	“	Essex	1960	590	1979-92	105	13
701	41.9361	-78.8376	PA	McKean	1975	590	1986-91	100	6
702	41.7519	-78.7540	“	McKean	1975	615	1986-91	148	6
703	41.9067	-78.8145	“	McKean	1975	595	1979-92	117	14
706	41.1768	-75.6076	“	Lackawanna	1960	667	1979-92	200	14
707	41.7076	-78.0127	“	Potter	1975	667	1979-92	145	14
708	41.8944	-77.7036	“	Potter	1975	667	1982-92	226	11
719	39.9315	-77.8724	“	Franklin	--	672	1984-92	140	7
720	41.9815	-79.2360	“	Warren	1975	475	1984-92	100	10
721	41.8717	-78.9692	“	Warren	1975	672	1982-92	100	11
722	39.9442	-75.4457	“	Delaware	--	117	1984-92	110	9
723	40.2538	-76.5216	“	Lebanon	1986	184	1984-92	97	9
820	38.6666	-79.9070	WV	Randolph	1980	1217	1983-92	156	10
821	38.6165	-79.7300	“	Pocahontas	1980	1240	1983-92	123	10
822	38.6874	-79.7620	“	Randolph	1980	1217	1983-92	118	10

Table A2. Estimation of population levels for scale insects and Neonectria on a 0-5 and 0-4 point scale respectively. For scale insects, populations were assessed based on the density of white, waxy secretion produced in abundance by scale insects. *Neonectria* population density estimates derive from the presence of red, sexual spore-bearing structures called perithecia.

Density code	**Qualitative assessment**	**Corresponding scale insect density/appearance**	**Corresponding *Neonectria* density/appearance**
0	None	No colonies visible	Perithecia absent
1	Trace	1 to a few scattered colonies; < 2 larger colonies visible	A few localized perithecia present, often within scattered circular infections
2	Light	Light to moderate scattered colonies, a few larger colonies may be present	Scattered moderate fruiting
3	Moderate	Many colonies; substantial number of larger colonies may be present	Many isolated circular infections present; abundant perithecia
4	Heavy	Many large colonies present, with some coalescing	Large areas of bark with heavy fruiting; parts of tree conspicuously red or brownish
5	Very heavy (scale only)	Much of the bark conspicuously white with wax	

Table A3. List and descriptions of exogenous effects used in model selection to explain variance across sites in density dependent slopes, carrying capacities and error magnitude. A subset of the terms (those that vary annual) were also used as potential predictors of error variance not explained by density dependence. Category order reflects *a priori* determinations of probable importance to BBD dynamics. Dormancy applies primarily to insect populations as fungi are known to grow throughout the year, conditions permitting (Dukes et al 2009).

Category		Variable name	Description	Dates	Proposed mechanism
Biotic interactions		INSECT	Mean population density of scale insects (0-5 index)	NA	Competition or facilitation by disease agent associate (Ehrlich 1934; Shigo 1964; Houston, 1992)
		NEONECTRIA	Mean population density fungal associate (0-4 index)	NA	“
Resource limitation		TREECOUNT	Count of sampled living beech trees	NA	Proxy for beech density, representing stand-level resource base
		DBH	Mean diameter at breast height (cm) of all living beech sampled	NA	Larger trees support higher disease agent population, and may be more susceptible to attack (Gove 1996; Houston 1994)
Climate	Growing season	TSUM	Thermal sum (deg. days > 5° C)	Mar. 15 - Oct. 15	Development, growth and fecundity linked to temperature for all poikilotherms through temperature-dependent metabolic rate (Huey 2001)
		EARLYPRECIP	Precipitation (cm) during development and reproduction	Mar. 15 - Sept. 15	Water availability linked to host quality (e.g. tissue moisture content; 2° chemistry); desiccation rates for insects, perithecial production and sporulation for fungi.
	Dormant season	LATEPRECIP	Total precipitation (cm) during per late summer/ early Fall	Aug. 15 - Nov. 1	For scale insects, heavy rainfall during this period may wash vulnerable early instars down tree (Houston 1994). High moisture during this time may aid fungal growth while tree defenses are lower (Dukes et al. 2009)
		CHILL	# of non-overlapping 5-day periods with mean temp. < -7°C	Oct. 15 - Mar. 31	Winter survival in Heteropterans and other insect is sensitive to accumulated cold at moderate sub-zero temperatures (Powell 1976). Effect on *Neonectria* unclear.
		MINWINTER	Coldest recorded winter temperature	"	Probability of exceeding lower lethal temperature.
		DAYS-15	Min. temp < -15°C	"	Correlated with accumulated cold days and the probability of exceeding lower lethal temp (Powell 1976).
		DAYS-34	Min. temp < -34°C	"	Lower lethal temperature for *C. fagisuga* under laboratory conditions (Barter 1953)
		SNOWABOVE10	Day count snow depth > 10 cm	"	Snowpack could provide a refugium from extreme cold and allow population to persist on the roots and lower bole (Dukes et al. 2009).
		EARLYPRECIP	Total precipitation (cm) through much of Spring	Mar. 15 - May 15	As for LATEPRECIP
Disease ontogeny		DURATION	Years of BBD infection	NA	Feedbacks with forest dynamics (potentially linked to management), changes in tree resistance, or slow-developing community dynamics

Table A4. Top three models selected using all possible regressions for each response variable considered, ranked by AIC_c. ΔAIC values are relative to the best model (ΔAIC=0) within each response variable; weights correspond to model likelihood given the data. Models in bold represent the top consensus models also favored by hierarchical selection (see Methods).

	Response variable	Explanatory variable	ΔAIC_c	AIC_c weight	R^2
Scale insects	Slope	**EARLYPRECIP, DURATION, DURATION^2**	0.00	0.66	0.77
		EARLYPRECIP, DBH, DURATION, DURATION^2	2.04	0.24	0.79
		DURATION, DURATION^2	3.71	0.10	0.69
	K	SNOWABOVE10, EARLYPRECIP, DBH	0.00	0.46	0.58
		EARLYPRECIP, DBH	0.83	0.30	0.50
		DAYSBELOW-10, EARLYPRECIP, DBH	1.37	0.23	0.56
	MSE	EARLYPRECIP, DURATION, TSUM, TREECOUNT	0.00	0.44	0.69
		EARLYPRECIP, TSUM, DURATION	0.84	0.29	0.62
		EARLYPRECIP, TSUM, TREECOUNT	1.01	0.27	0.62
	ε	**EARLYPRECIP, SNOWABOVE10**	0.00	0.40	0.07
		EARLYPRECIP, SNOWABOVE10, TSUM	0.24	0.35	0.08
		EARLYPRECIP, TSUM, MINWINTERTEMP	0.96	0.25	0.08
Neonectria	Slope	**DURATION, DURATION^2**	0.00	0.68	0.41
		TREECOUNT, DURATION, DURATION^2	2.53	0.19	0.49
		DAYSBELOW-34, DURATION, DURATION^2	3.40	0.12	0.46
	K	**DURATION, DURATION^2, LATEPRECIP**	0.00	0.64	0.79
		LATEPRECIP, SNOWABOVE10	2.28	0.20	0.66
		LATEPRECIP, SNOWABOVE10, TREECOUNT	2.80	0.16	0.74
	MSE	**DBH**	0.00	0.39	0.06
		EARLYPRECIP	0.45	0.31	0.03
		INSECT	0.48	0.30	0.03
	ε	EARLYPRECIP, TSUM, MINWINTERTEMP	0.00	0.40	0.10
		EARLYPRECIP	0.36	0.33	0.05
		EARLYPRECIP, TSUM	0.81	0.27	0.06

Table A5. Parameter estimates from top (bolded) models from Table A4.

	Response variable	Explanatory variable	Estimate	SE	Mean Square	Df	Signif. code
Scale insects	Slope	DURATION	0.01	0.01	0.04	1	.
		DURATION^2	0.00	0.00	0.72	1	**
		EARLYPRECIP	-0.019	0.0073	0.03	1	*
		Residuals	-	-	0.01	19	-
	K	EARLYPRECIP	-0.056	0.0268	0.41	1	*
		DBH	0.058	0.0137	3.28	1	***
		Residuals	-	-	0.18	20	-
	MSE	TSUM	-0.0003	0.0001	0.03	1	***
		EARLYPRECIP	0.0072	0.0030	0.02	1	*
		DURATION	-0.0015	0.0006	0.01	1	*
		Residuals	-	-	0.00	19	-
	ε	SNOWABOVE10	0.002	0.001	0.45	1	**
		EARLYPRECIP	0.010	0.004	0.50	1	*
		Residuals	-	-	0.08	155	-
Neonectria	Slope	DURATION	0.040	0.015	0.44	1	*
		DURATION^2	-0.001	0.0003	0.08	1	*
		Residuals	-	-	0.06	12	-
	K	LATEPRECIP	0.228	0.049	3.92	1	***
		DURATION	0.096	0.024	2.51	1	**
		DURATION^2	-0.002	0.001	0.01	1	**
		Residuals	-	-	0.16	11	-
	MSE	DBH	-0.005	0.005	0.02	1	n.s.
		Residuals	-	-	0.02	13	-
	ε	EARLYPRECIP	0.014	0.007	0.71	1	*
		Residuals	-	-	0.17	87	-

***P<0.001; **P<0.01; *P<0.05; '.' P<0.10; n.s.= not significant.

SUPPLEMENTAL FIGURES

Figure A1. Locations of plots (red circles) initially established by David Houston of the USDA Forest Service and state cooperators between 1979 and 1985 and were monitored approximately yearly until 1992. See Table A1 for details. Beech (gray) and BBD distribution (beige) derived from county-level data within the US (data from Morin et al. 2007); Canadian distribution is approximate after Lovett et al. (2006)

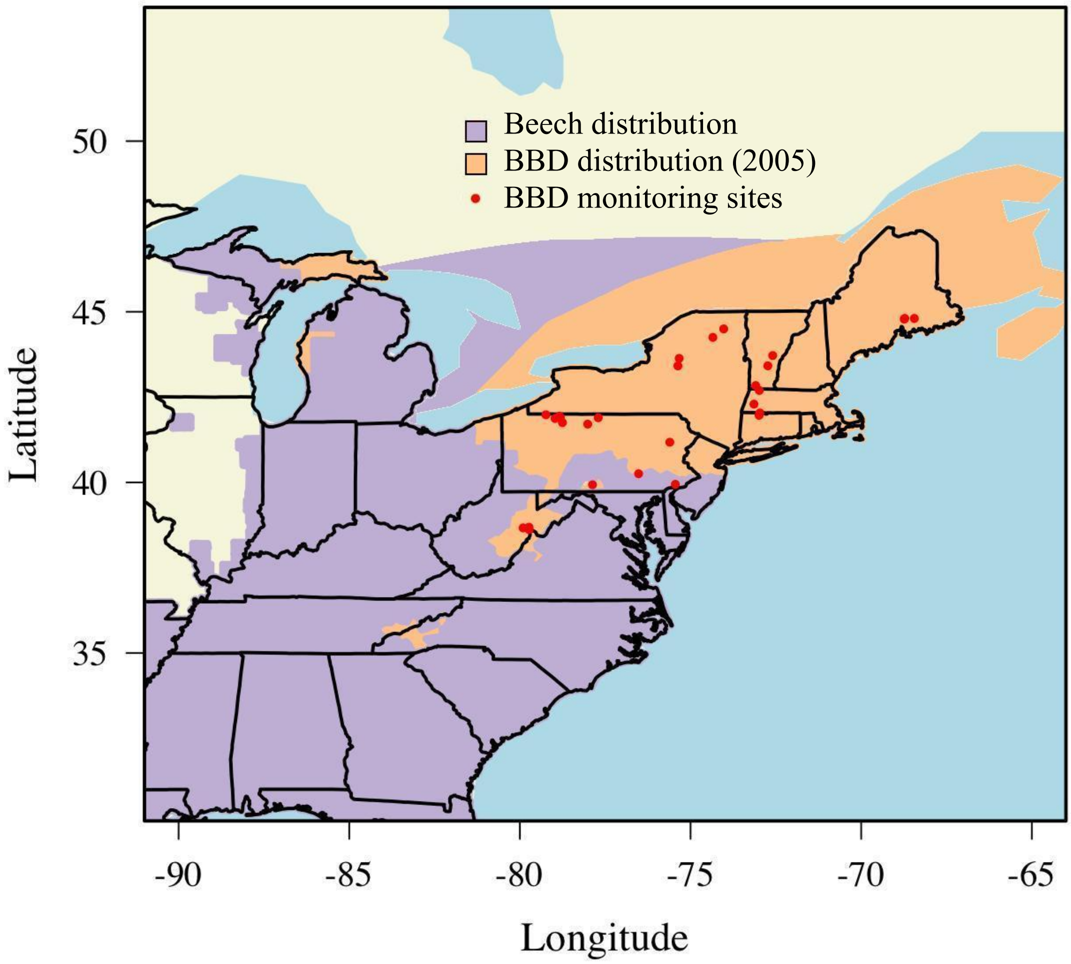


Figure A2. Autocorrelation functions (ACF) for scale insects (left) and *Neonectria* (right). Bars are mean values across sites; error bars show SEM.

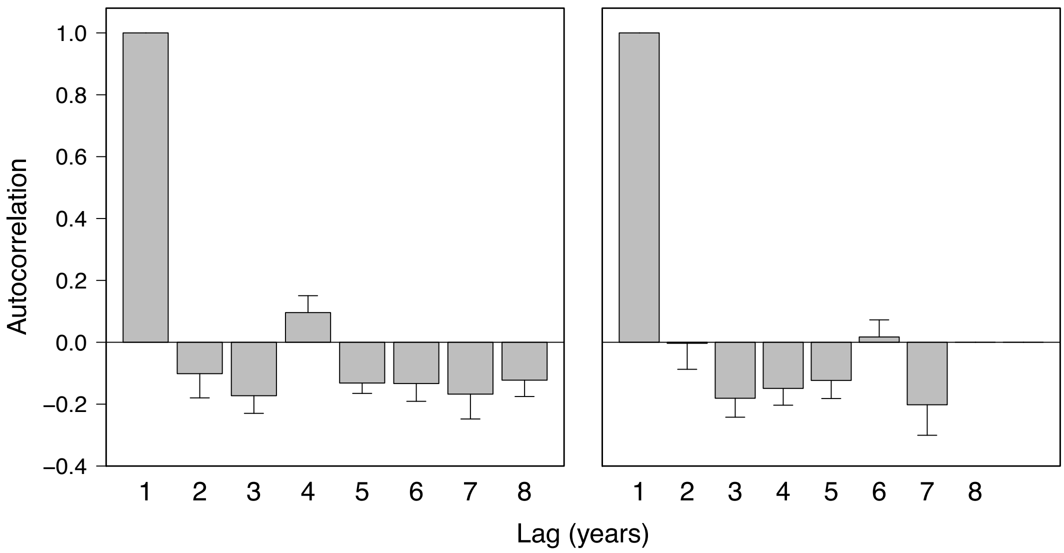


Figure A3. Temporal cross-correlation function for scale insects (left) and *Neonectria* (right). Bars are mean correlation coefficients across sites; error bars show SEM.

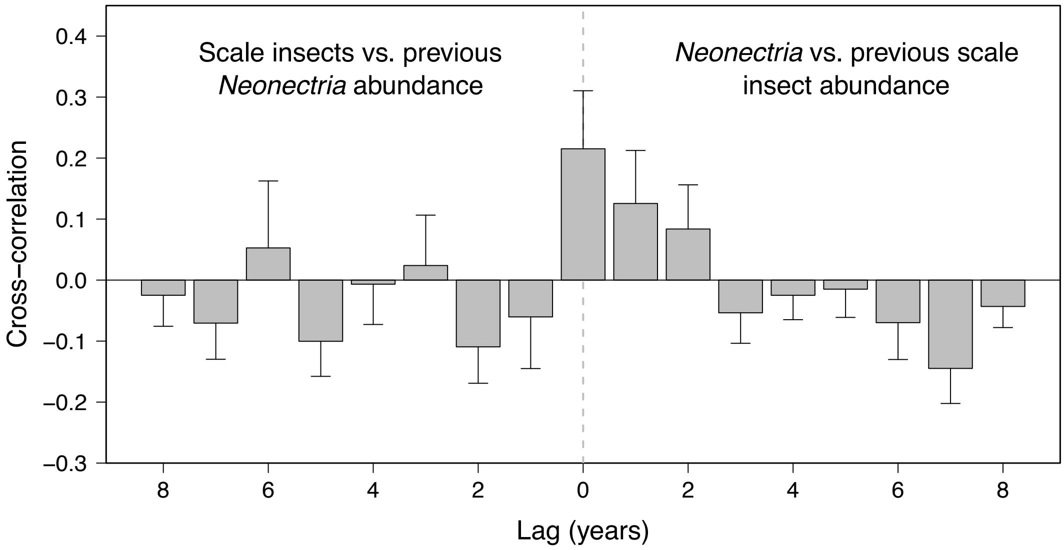


Figure A4. Spline correlograms showing spatial autocorrelation among sites for scale insects (left) and *Neonectria* (right).

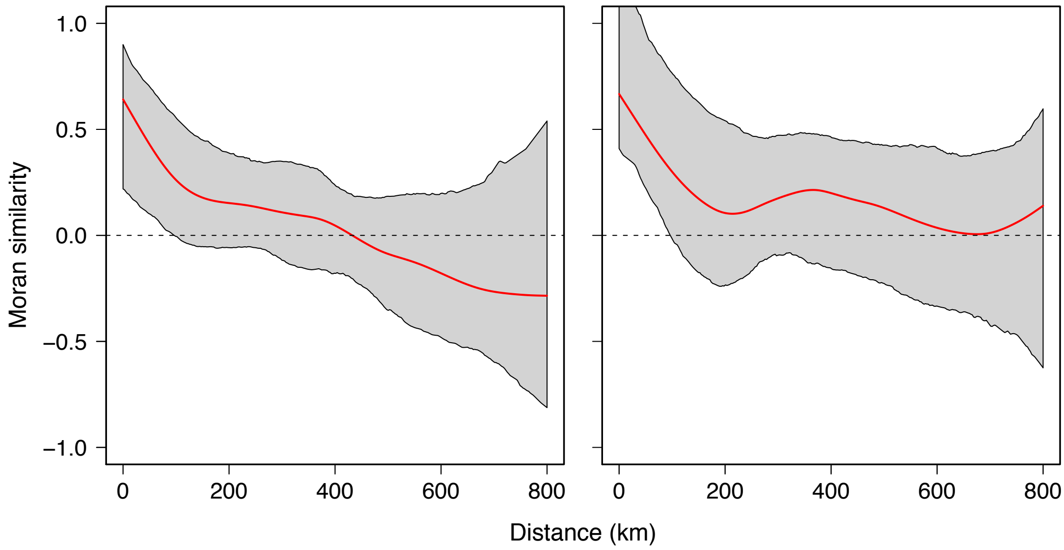
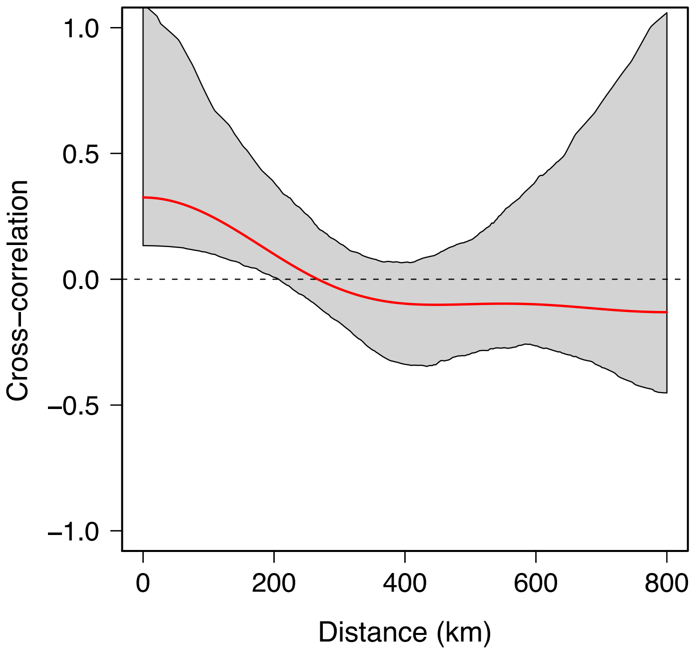


Figure A5. Spline correlogram depicting spatial cross-correlation among scale insects and *Neonectria* populations.



SUPPLEMENTAL LITERATURE CITED

Barter, G. 1953. Additional observations on the beech scale in New Brunswick. - Bi-Mon. Prog. Rep. Div. For. Biol. Dep. Agric. Can. 9: 1-2.

Ehrlich, J. 1934. The beech bark disease: A *Nectria* disease of *Fagus*, following *Cryptococcus fagi* (Baer.). - Canadian Journal of Research 10: 593-692.

Gove, J. H. and Houston, D. R. 1996. Monitoring the growth of american beech affected by beech bark disease in Maine using the Kalman filter. - Environmental and Ecological Statistics 3: 167-187.

Houston, D. R. 1992. A host-stress-saprogen model for forest dieback-decline diseases. - American Phytopathology Society.

Houston, D. R. 1994. Major new tree disease epidemics - beech bark disease. - Annual Review of Phytopathology 32: 75-87.

Huey, R. B. and Berrigan, D. 2001. Temperature, demography, and ectotherm fitness. - American Naturalist 158: 204-210.

Lovett, G. M., et al. 2006. Forest ecosystem responses to exotic pests and pathogens in eastern North America. - Bioscience 56: 395-405.

Morin, R. S., et al. 2007. Spread of beech bark disease in the eastern United States and its relationship to regional forest composition. - Canadian Journal of Forest Research 37: 726–736.

Powell, W. and Parry, W. H. 1976. Effects of temperature on overwintering populations of green spruce aphid *Elatobium abietinum*. - Annals of Applied Biology 82: 209-219.

Shigo, A. L. 1964. Organism interactions in beech bark disease. - Phytopathology 54: 263-269.