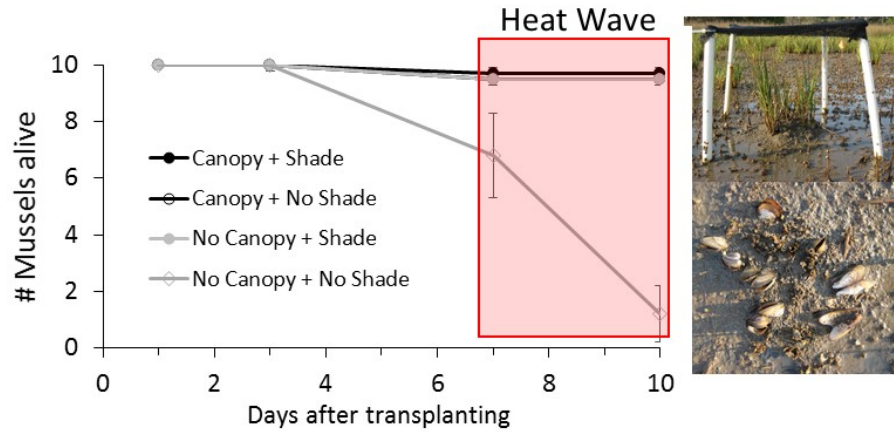


## Foundation species, biodiversity hotspots, and landscape-scale multifunctionality

### Supplementary Materials

#### **Supplementary Methods 1.** *Can mussels survive in marsh platforms without cordgrass?*

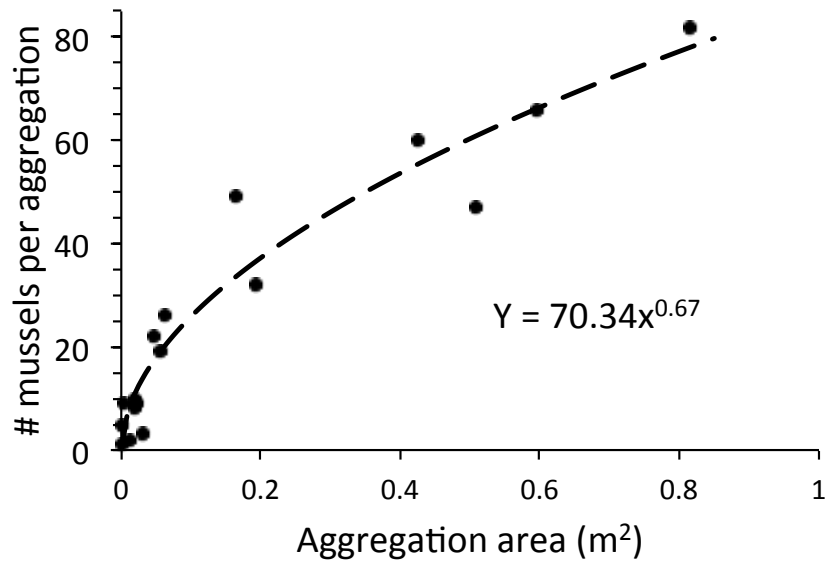
To assess whether cordgrass alleviates temperature stress to facilitate mussels in southeastern US salt marshes as shown in New England fringing salt marshes (1) and identify whether interactions among cordgrass and mussels are an example of hierarchical facilitation (1), we conducted a field experiment in a Sapelo Island marsh platform in July 2011. Specifically, we marked 24 plots spaced >1m apart in a recently-formed mudflat and planted a cordgrass transplant of a standard size (20cm<sup>3</sup> plug of roots + marsh soil and 8-10 cordgrass stems) in each. The experiment was conducted in a mudflat, rather than in a healthy stand of cordgrass, to prevent neighboring vegetation from influencing the efficacy of experimental treatments. Each plot was then haphazardly assigned one of four treatments: Canopy + Shade, Canopy + No Shade, No Canopy + Shade, or No Canopy + No Shade. The live cordgrass stems (i.e. the canopy) was left unmanipulated in Canopy plots and removed with shears in No Canopy plots. Experimental shades constructed using PVC corner posts and a sheet of landscape fabric were placed 40cm above Shade plots, while No Shade plots were left unmanipulated. PAR and iButton temperature readings collected at the marsh surface in Shade plots and healthy cordgrass monocultures in the marsh platform indicate that Shades effectively mimicked the shading provided the cordgrass canopy at this elevation (i.e. 70% light reduction). We then transplanted 10 mussels (size: 50-70mm shell length) into each plot in a cluster to mimic natural aggregations. After 1, 3, 7 and 10 days, we scored mussel survival. Mussel mortality occurred between days 7 and 10 during a summer heat wave that was within the range of temperatures typically of the southeastern US in late summer.



**Supplementary Figure 1.** Effects of natural and experimental shade on mussel survival. Results of a field experiment manipulating cordgrass canopy and shade (canopy mimic) presence and an example of our experimental Canopy + Shade treatments and dead mussels at the end of the experiment. The number of mussels, out of 10 transplanted, remaining alive over time are shown as the mean  $\pm$  SE of 6 replicate plots per treatment. The duration of the heat wave, when iButtons revealed daytime marsh surface temperatures outside of shade and canopy experimental treatments exceeded 46°C but were less than 42°C within them, is indicated by the red box.

**Supplementary Methods 2:** *Relationship between mussel aggregation area and the number of mussels per aggregation*

To estimate the range of densities with which mussels aggregate in marsh platforms and establish the functional relationship between aggregation area (defined by the perimeter of the outermost mussels in each aggregation) and the number of mussels per aggregation, we identified 17 aggregations that spanned the entire natural size range in one representative marsh platform site on Sapelo Island, GA. At each mound, we measured the aggregation diameter and then extracted and counted every mussel that was present. The number of mussels per aggregation ranged from 0 to 82 mussels. Comparison of linear, log, hyperbolic and log models revealed that the relationship between aggregation area and the number of mussels was best-fit by a power law function, shown in the figure below.



**Supplementary Figure 2.** Mussel area – density relationship. Relationship between aggregation area and the number of mussels within each for 17 aggregations extracted at one marsh platform field site on Sapelo Island, GA.

**Supplementary Table 1.** Summary of five models describing the relationship between the number of mussels added (M) and each ecosystem function and multifunctionality response (Y). The best-fit model, according to AICc model comparisons, for each response is highlighted in bold.

Response Variable	Model	Parameter estimates			AICc	delta AIC	AICc weights
		a	b	Z			
Soil Accretion	Null, y= a	3.3	NA	NA	104.9	44.15	1.3*10 <sup>-10</sup>
	Linear, y=a + bM	2	0.07	NA	73.9	13.13	7.3*10 <sup>-4</sup>
	<b>Log, y=a +b*log(M+1)</b>	<b>0.49</b>	<b>1.29</b>	<b>NA</b>	<b>60.8</b>	<b>0</b>	<b>0.52</b>
	Hyperbolic, y= a*M/(b + M)	7.08	10.42	NA	64.8	4.08	6.8*10 <sup>-3</sup>
	Power, y=a+ bM <sup>Z</sup>	0.89	0.77	0.46	61.2	0.48	0.41
Infiltration**	Null, y= a	15.45	NA	NA	231.2	20.03	3.8*10 <sup>-5</sup>
	<b>Linear, y=a + bM</b>	<b>0</b>	<b>0.78</b>	<b>NA</b>	<b>211.1</b>	<b>0</b>	<b>0.85</b>
	Log, y=a +b*log(M+1)	0	8.56	NA	221.1	9.93	5.9*10 <sup>-3</sup>
	Power, y=a+ bM <sup>Z</sup>	6.34	0.000068	3.14	214.6	3.45	0.15
Decomposition	Null, y= a	0.61	NA	NA	-20.3	5.02	3.8*10 <sup>-2</sup>
	<b>Linear, y=a + bM</b>	<b>0.55</b>	<b>0.0029</b>	<b>NA</b>	<b>-25.3</b>	<b>0</b>	<b>0.46</b>
	*Log, y=b*log(M+1)	0.50	0.052	NA	-24.9	0.47	0.37
	Hyperbolic, y= a*M/(b + M)	0.66	0.18	NA	1.1	26.41	8.5*10 <sup>-7</sup>
	*Power, y= bM <sup>Z</sup>	0.50	0.044	0.4	-22.8	2.49	0.13
Aboveground <i>Spartina</i> biomass	Null, y= a	68.48	NA	NA	220.8	6.51	2.4*10 <sup>-2</sup>
	Linear, y=a + bM	57.64	0.53	NA	216.2	1.97	0.23
	<b>*Log, y=b*log(M+1)</b>	<b>44.81</b>	<b>10.7</b>	<b>NA</b>	<b>214.3</b>	<b>0</b>	<b>0.63</b>
	Hyperbolic, y= a*M/(b + M)	17.08	-8.13	NA	263.2	48.96	1.5*10 <sup>-11</sup>
	*Power, y=a+ bM <sup>Z</sup>	49.08	5.82	0.48	217.7	3.44	0.11
Benthic algae biomass	<b>Null, y= a</b>	<b>16.56</b>	<b>NA</b>	<b>NA</b>	<b>104.9</b>	<b>0</b>	<b>0.39</b>
	Linear, y=a + bM	16.33	0.01	NA	107.1	2.24	0.13
	Log, y=a +b*log(M+1)	15.47	0.49	NA	104.9	0.06	0.38
	Hyperbolic, y= a+ M/ (b + M)	17.51	0.19	NA	152.6	47.71	1.7*10 <sup>-7</sup>
	Power, y=a+ bM <sup>Z</sup>	14.83	1.43	0.13	107.5	2.61	0.11
Invertebrate biomass	Null, y= a	28.08	NA	NA	241.53	33.45	2.9*10 <sup>-8</sup>
	<b>Linear, y=a + bM</b>	<b>5.29</b>	<b>1.15</b>	<b>NA</b>	<b>208.08</b>	<b>0</b>	<b>0.53</b>
	Log, y=a +b*log(M+1)	0	14.47	NA	222.74	14.66	3.4 *10 <sup>-4</sup>
	Hyperbolic, y= a*M/(b + M)	373.3	232.8	NA	208.89	0.81	0.35
	Power, y=a+ bM <sup>Z</sup>	4.89	1.28	0.97	210.98	2.9	0.12

\* y- intercept set to 0; \*\* Power function was not fit; \*\*\* Hyperbolic function was not fit

**Supplementary Table 2.** Summary of five models describing the effect mussels on multifunctionality, where M refers to the number of mussels added, Y refers to each response variable. The best-fit model, according to AICc model comparisons, are in bold.

Response Variable	Model	Parameters estimates					
		a	b	z	AICc	delta AIC	AICc weights
<b>Average Multifunctionality</b>							
	Null, $y = a$	53.39	NA	NA	200.6	48.9	$1.9 \times 10^{-11}$
	Linear, $y = a + bM$	40.75	0.613	NA	154.2	2.5	0.22
	Log, $y = a + b \cdot \log(M+1)$	29.54	0.107	NA	165.6	13.9	$7.4 \times 10^{-4}$
	Hyperbolic, $y = a \cdot M / (b + M)$	72.42	2.12	NA	202.9	51.9	$4.2 \times 10^{-12}$
	<b>Power, <math>y = a + bM^z</math></b>	<b>36.30</b>	<b>2.84</b>	<b>0.66</b>	<b>151.7</b>	<b>0</b>	<b>0.78</b>
<b>Threshold Indices: the number of functions performed above a % of maximum functioning performance threshold</b>							
<b>&gt;10% threshold</b>							
	Null, $y = a$	5.30	NA	NA	34.2	15.7	$2.4 \times 10^{-4}$
	<b>Linear, <math>y = a + bM</math></b>	<b>5.04</b>	<b>0.01</b>	<b>NA</b>	<b>18.5</b>	<b>0</b>	<b>0.63</b>
	Log, $y = a + b \cdot \log(M + 1)$	4.80	0.23	NA	21.3	2.8	0.15
	Hyperbolic, $y = a \cdot M / (b + M)$	5.53	0.15	NA	20.6	2.1	0.22
	*Power, $y = a + bM^z$	4.95	0.05	0.68	100.8	82.3	$8.4 \times 10^{-19}$
<b>&gt;20% threshold</b>							
	Null, $y = a$	5.04	NA	NA	48.2	17.6	$8.9 \times 10^{-5}$
	Linear, $y = a + bM$	4.68	0.02	NA	33.2	2.6	0.16
	<b>Log, <math>y = a + b \cdot \log(M + 1)</math></b>	<b>4.30</b>	<b>0.33</b>	<b>NA</b>	<b>30.6</b>	<b>0</b>	<b>0.60</b>
	Hyperbolic, $y = a \cdot M / (b + M)$	2.42	-2.05	NA	133.1	102.5	$3.3 \times 10^{-23}$
	*Power, $y = a + bM^z$	4.35	0.26	0.41	32.4	1.8	0.24
<b>&gt;30% threshold</b>							
	Null, $y = a$	4.13	NA	NA	74.9	19.8	$2.7 \times 10^{-5}$
	Linear, $y = a + bM$	3.38	0.04	NA	47.6	2.1	0.19
	<b>Log, <math>y = a + b \cdot \log(M + 1)</math></b>	<b>2.58</b>	<b>0.70</b>	<b>NA</b>	<b>40.5</b>	<b>0</b>	<b>0.54</b>
	Hyperbolic, $y = a \cdot M / (b + M)$	5.42	2.09	NA	83.3	33.5	$2.9 \times 10^{-8}$
	*Power, $y = a + bM^z$	2.71	0.34	0.52	41.3	1.4	0.27
<b>&gt;40% threshold</b>							
	Null, $y = a$	3.78	NA	NA	82.5	34.4	$3.1 \times 10^{-8}$
	Linear, $y = a + bM$	2.95	0.04	NA	61.6	13.5	$1.1 \times 10^{-3}$
	<b>Log, <math>y = a + b \cdot \log(M+1)</math></b>	<b>1.95</b>	<b>0.83</b>	<b>NA</b>	<b>48.1</b>	<b>0</b>	<b>0.91</b>
	Hyperbolic, $y = a \cdot M / (b + M)$	5.32	2.43	NA	76.1	28.0	$7.6 \times 10^{-7}$
	*Power, $y = a + bM^z$	2.11	0.62	0.41	52.7	4.6	0.09
<b>&gt;50% threshold</b>							
	Null, $y = a$	3.17	NA	NA	84.4	32.9	$4.3 \times 10^{-8}$
	Linear, $y = a + bM$	2.22	0.05	NA	52.4	0.9	0.38
	Log, $y = a + b \cdot \log(M+1)$	1.37	0.81	NA	58.3	6.8	0.02
	Hyperbolic, $y = a \cdot M / (b + M)$	5.55	7.16	NA	76.4	24.9	$2.3 \times 10^{-6}$
	<b>Power, <math>y = a + bM^z</math></b>	<b>1.88</b>	<b>0.21</b>	<b>0.66</b>	<b>51.5</b>	<b>0</b>	<b>0.60</b>
<b>&gt;60% threshold</b>							
	Null, $y = a$	2.87	NA	NA	88.0	31.3	$1.1 \times 10^{-8}$
	Linear, $y = a + bM$	1.87	0.05	NA	59.9	3.2	0.14

	Log, $y=a + b \cdot \log(M+1)$	0.89	0.90	NA	59.7	3.0	0.16
	Hyperbolic, $y= a \cdot M / (b + M)$	5.64	9.80	NA	69.1	12.4	$1.4 \times 10^{-3}$
	<b>Power, <math>y=a+ bM^z</math></b>	<b>1.34</b>	<b>0.33</b>	<b>0.57</b>	<b>56.7</b>	<b>0</b>	<b>0.70</b>
>70% threshold							
	Null, $y= a$	2.13	NA	NA	87.1	21.7	$8.6 \times 10^{-6}$
	<b>Linear, <math>y=a + bM</math></b>	<b>1.21</b>	<b>0.04</b>	<b>NA</b>	<b>65.4</b>	<b>0</b>	<b>0.73</b>
	Log, $y=a + b \cdot \log(M+1)$	0.43	0.77	NA	70.3	4.9	0.06
	Hyperbolic, $y= a \cdot M / (b + M)$	4.57	12.0	NA	73.4	8	0.01
	Power, $y=a+ bM^z$	1.01	0.13	0.76	68.0	2.6	0.20
>80% threshold							
	Null, $y= a$	1.43	NA	NA	87.6	19.5	$3.9 \times 10^{-5}$
	<b>Linear, <math>y=a + bM</math></b>	<b>0.53</b>	<b>0.04</b>	<b>NA</b>	<b>68.1</b>	<b>0</b>	<b>0.68</b>
	Log, $y=a + b \cdot \log(M+1)$	-0.23	0.75	NA	72.9	4.8	0.06
	Hyperbolic, $y= a \cdot M / (b + M)$	8.65	96.27	NA	71.7	3.6	0.11
	Power, $y=a+ bM^z$	0.53	0.04	1.01	71.1	3.0	0.15
>90% threshold							
	Null, $y= a$	0.78	NA	NA	77.4	23.1	$7.7 \times 10^{-6}$
	Linear, $y=a + bM$	0.05	0.04	NA	57.1	2.8	0.20
	Log, $y=a + b \cdot \log(M+1)$	-0.34	0.51	NA	69.2	14.9	$4.6 \times 10^{-4}$
	<b>Power, <math>y=a+ bM^z</math></b>	<b>0.33</b>	<b>0.00001</b>	<b>2.88</b>	<b>54.3</b>	<b>0</b>	<b>0.80</b>

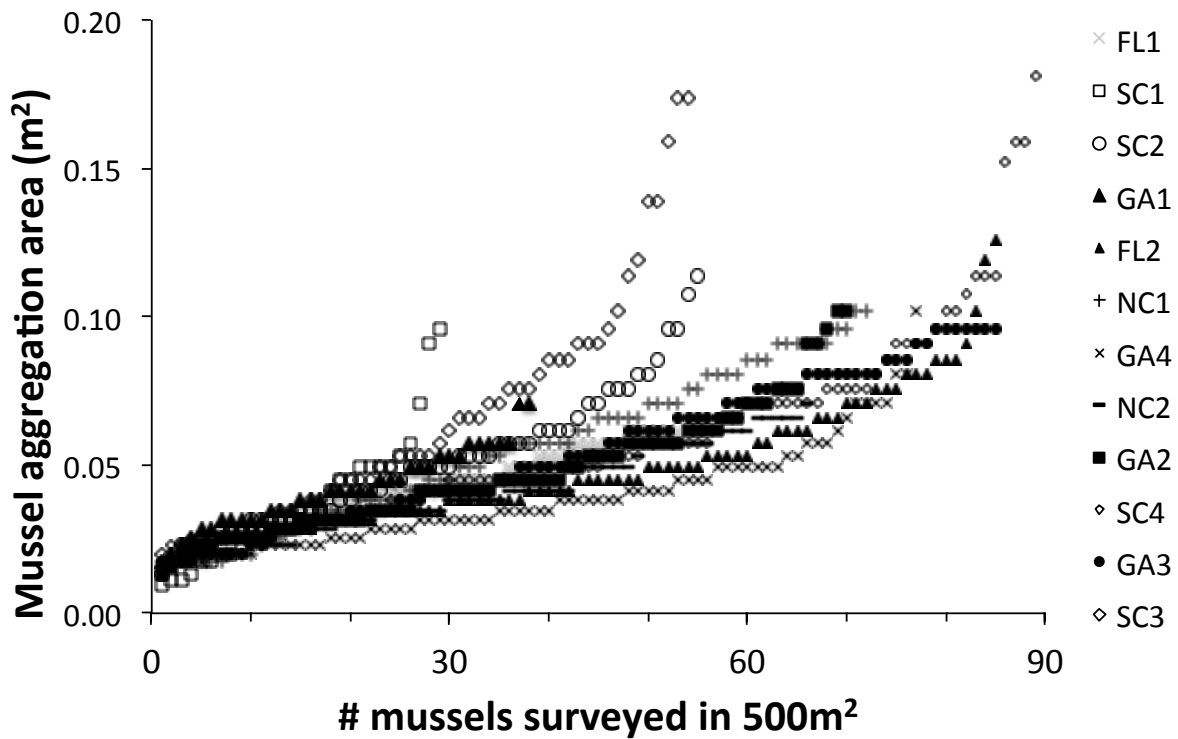
**Supplementary Table 3.** Summary of five models describing the relationship between the number of mussels added and each invertebrate functional group response measured in experimental plots, where M refers to the number of mussels added, Y refers to each response variable. The best-fit model, according to AICc model comparisons are highlighted in bold.

Response Variable	Model Type	Parameters estimates					
		A	b	z	AICc	delta AIC	AICc weight
Mud crabs							
	Null, $y= a$	0.67	NA	NA	61.9	15.34	$1.7 \cdot 10^{-4}$
	Linear, $y=a + bM$	0.23	0.022	NA	47.9	1.28	0.19
	<b>*Log, <math>y=b \cdot \log(M+1)</math></b>	<b>0</b>	<b>0.33</b>	<b>NA</b>	<b>46.6</b>	<b>0</b>	<b>0.36</b>
	Hyperbolic, $y= a \cdot M / (b + M)$	2.56	37.29	NA	48.5	1.91	0.14
	*Power, $y= bM^z$	0	0.16	0.56	46.9	0.29	0.31
Marsh crabs							
	Null, $y= a$	0.75	NA	NA	93.2	8.75	$5.0 \cdot 10^{-3}$
	Linear, $y=a + bM$	0.032	0.036	NA	84.7	0.21	0.36
	*Log, $y=b \cdot \log(M+1)$	0	0.42	NA	85.6	1.08	0.23
	Hyperbolic, $y= a \cdot M / (b + M)$	0.37	-7.28	NA	97.4	12.88	$6.4 \cdot 10^{-4}$
	<b>*Power, <math>y=a+ bM^z</math></b>	<b>0</b>	<b>0.074</b>	<b>0.83</b>	<b>84.5</b>	<b>0</b>	<b>0.40</b>
Snails**							
	Null, $y= a$	183.92	NA	NA	259.7	0.81	0.34
	<b>Linear, <math>y=a + bM</math></b>	<b>197.7</b>	<b>-0.69</b>	<b>NA</b>	<b>258.9</b>	<b>0</b>	<b>0.52</b>
	Log, $y=a + b \cdot \log(M+1)$	197.78	-6.37	NA	261.5	2.63	0.14
	Hyperbolic, $y= a \cdot M / (b + M)$	-6.21	41.21	NA	323.47	64.61	$4.8 \cdot 10^{-15}$
Adult fiddler crabs							
	Null, $y= a$	7.08	NA	NA	116.31	2.25	0.16
	Linear, $y=a + bM$	7.77	0.035	NA	115.6	1.54	0.23
	<b>Log, <math>y=a + b \cdot \log(M+1)</math></b>	<b>8.73</b>	<b>-0.76</b>	<b>NA</b>	<b>114.06</b>	<b>0</b>	<b>0.51</b>
	Hyperbolic, $y= a + M / (b + M)$	6.14	-0.38	NA	136.19	22.13	$7.9 \cdot 10^{-6}$
	Power, $y=a+ bM^z$	8.54	-0.55	0.41	117.39	3.33	$9.5 \cdot 10^{-3}$
Juvenile fiddler crabs							
	Null, $y= a$	28.08	NA	NA	241.53	33.45	$2.9 \cdot 10^{-8}$
	<b>Linear, <math>y=a + bM</math></b>	<b>5.29</b>	<b>1.15</b>	<b>NA</b>	<b>208.08</b>	<b>0</b>	<b>0.53</b>
	Log, $y=a + b \cdot \log(M+1)$	0	14.47	NA	222.74	14.66	$3.4 \cdot 10^{-4}$
	Hyperbolic, $y= a \cdot M / (b + M)$	373.3	232.8	NA	208.89	0.81	0.35
	Power, $y=a+ bM^z$	4.89	1.28	0.97	210.98	2.9	0.12
Functional richness							
	Null, $y= a$	4.67	NA	NA	72.0	30.04	$1.91 \cdot 10^{-7}$
	Linear, $y=a + bM$	4.16	0.026	NA	60.2	18.27	$6.87 \cdot 10^{-5}$
	<b>Log, <math>y=a + b \cdot \log(M+1)</math></b>	<b>3.35</b>	<b>0.61</b>	<b>NA</b>	<b>42.0</b>	<b>0</b>	<b>0.64</b>
	Hyperbolic, $y= a \cdot M / (b + M)$	5.43	0.52	NA	83.9	41.92	$5.03 \cdot 10^{-10}$
	Power, $y=a+ bM^z$	2.66	1.09	0.23	43.1	1.13	0.36
Functional diversity, inverse Simpson's index							
	Null, $y= a$	1.59	NA	NA	19.4	25.0	$3.27 \cdot 10^{-5}$
	<b>Linear, <math>y=a + bM</math></b>	<b>1.39</b>	<b>0.01</b>	<b>NA</b>	<b>-5.6</b>	<b>0</b>	<b>0.54</b>
	Log, $y=a + b \cdot \log(M+1)$	1.19	0.18	NA	-1.4	4.2	0.07
	Hyperbolic, $y= a \cdot M / (b + M)$	1.84	0.69	NA	47.2	52.8	$1.83 \cdot 10^{-12}$
	Power, $y=a+ bM^z$	1.31	0.05	0.66	-5.0	0.6	0.40

\* y- intercept set to 0; \*\* Power function is not reported due to lack of model convergence

**Supplementary Methods 3:** *The number and size distribution of mussel aggregations across the twelve surveyed sites*

To characterize differences in the density and size distribution of mussel aggregations across salt marsh sites, we tallied and measured of every mussel aggregation observed within five, 5 × 20m belt transects run through marsh platforms at each site. Data from the five belt transects were pooled to provide representative measures of differences in mussel distribution across sites.

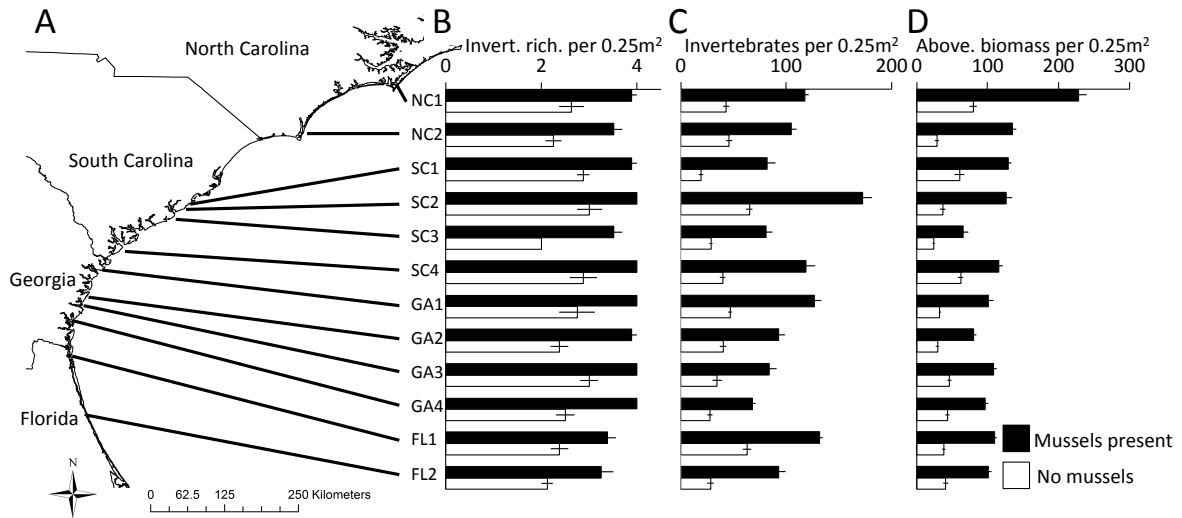


**Supplementary Figure 3.** The distribution of mussel aggregations observed across southeastern US salt marshes. At each site (denoted by different symbols), mussel aggregations are arranged in order of increasing area to demonstrate differences in the total density of mussel aggregation at each site (i.e. the maximum value on the x-axis) and size distribution of aggregations (i.e. distribution of values along the y-axis).



*Generality of the patch-scale effects of mussel aggregations on marsh invertebrates and ecosystem functioning across the southeastern US*

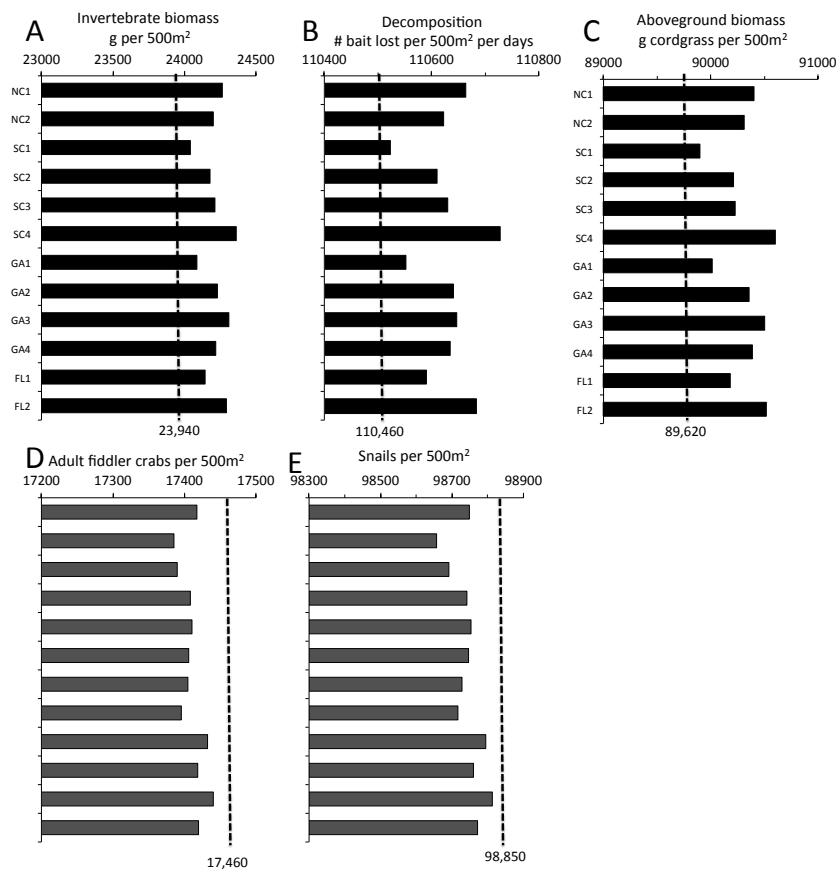
Results from characterizing the density of resident salt marsh invertebrate functional groups and aboveground biomass of cordgrass within replicate patch-size sampling frames ( $0.25\text{m}^2$ ,  $N=8$  per site) indicate mussel aggregations are stimulating functional group diversity and abundance and aboveground biomass similarly throughout this region.



**Supplementary Figure 4.** Distribution of surveyed marsh sites (A) and the patch-scale effects of mussel aggregations on resident invertebrate richness (B), total abundance (C), and aboveground biomass (D). Data are shown as the mean  $\pm$  standard error of values measured in 8 replicate  $0.25\text{m}^2$  sampling frames positioned in cordgrass-dominated marsh platform patches where mussel aggregations were either present (in back) and not present (in white).

*Landscape-scale effects of mussel aggregations on ecosystem functions and resident invertebrates across the southeastern US*

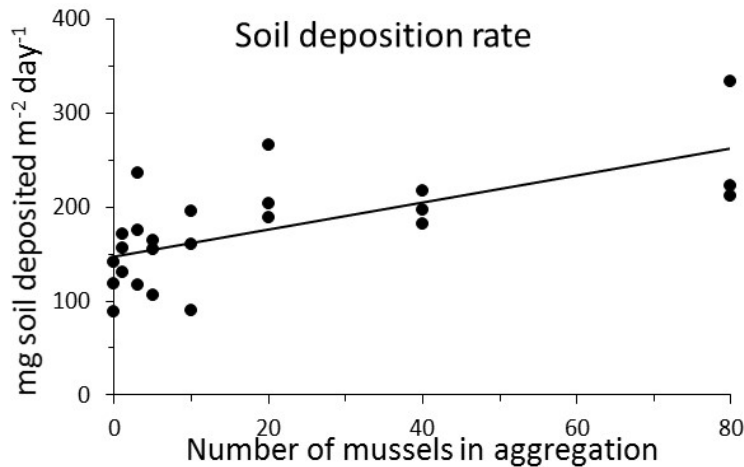
Using mapped mussel distributions and functional relationships derived from our patch-scale experiment, we estimated the total yield of ecosystem functions and number of resident invertebrates on the landscape ( $500\text{m}^2$ ) scale at each of the 12 salt marsh sites. Below are shown the three ecosystem functions (invertebrate biomass, decomposition and aboveground biomass) and two marsh invertebrates (adult fiddler crabs and snails) whose values did not vary markedly in response to differences in mussel distribution and are therefore not shown in the main text.



**Supplementary Information Figure 5.** Effects of mussel aggregations on the total yield of invertebrate biomass, decomposition and aboveground biomass ecosystem functions and adult fiddler crab and snail invertebrate functional groups at the landscape ( $500\text{m}^2$ ) scale.

**Supplementary Methods 5:** *Supplementary methods used to measure marsh ecosystem functions*

**Soil accretion:** To verify whether our method for quantifying soil accretion (i.e. inserting a small PVC rod into the marsh until it contacted the root mat) reflects differences in soil deposition, we secured a 7-cm diameter filter paper to the marsh with PVC anchor pins in a position that would not obstruct the filter-feeding activity of mussels or damage cordgrass stems within each plot (2, 3). After 48 hours, we collected, oven-dried, and weighed the papers. We found that our short-term soil deposition measures was positively and significantly correlated with soil accretion depth ( $R^2=0.46$ ,  $P=0.0002$ ), indicating our measures provide consistent evidence that mussels cause more sediment to accumulate on the marsh as aggregations become more dense.



**Supplementary Figure 6.** Summary of the effect of mussel density on soil deposition rate.



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