Appendix S1

The causes and consequences of pest population variability in agricultural landscapes

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Ecological Applications

Pest abundance and damage variables

RAIF technicians quantified the abundance of the olive fly (*Bactrocera oleae*), the olive moth (*Prays oleae*), and the European grapevine moth (*Lobesia botrana*) weekly throughout the growing season by monitoring traps baited with sex pheromones. The olive fly is monitored with yellow sticky traps, the olive moth with funnel traps, and the grapevine moth with delta traps. Three traps for the olive fly and two for the olive and the grapevine moth were placed in each field, and pests were collected and quantified after one week.

Technicians also quantified indicators for future pest damage that may inform insecticide spray decisions. For the olive fly, this constituted the percentage of olive fruits with visible signs of oviposition, calculated over a variable number of olives fruits per field depending on the destination of the product and the level of infestation (1000 olives per field for table olives and 200 or 400 olives per field for olive oil, depending on whether the degree of infestation is low [< 10% of olive fruits with visible signs of oviposition] or high [> 10% of olive fruits with visible signs of oviposition]). For the olive moth, future potential damage was quantified as the percentage of olive fruits with visible signs of oviposition, calculated over 200 olives per field. Finally, future potential grapevine moth damage was quantified as the percentage of grape clusters with visible signs of oviposition, calculated over 100 clusters per field.

Finally, technicians recorded measures of direct crop damage for the olive fly and grapevine moth (but not the olive moth). Olive fly damage was measured as the percentage of olives with exit holes, produced when full-grown fly larvae leave the olive fruits to pupate in the soil. For the grapevine moth, direct damage was measured as the percentage of grape clusters with holes chewed in fruits by caterpillars. Fruit feeding by the larvae of olive flies and grapevine moths injures the fruits and promotes fungal growth that ultimately both downgrades the quality of the harvest and reduces the quantity of the harvest.

Landscape context

We obtained data on the landscape context surrounding each field from two sources. First, we extracted information on different land uses from the CORINE Land Cover inventory. To measure landscape simplification, we calculated the proportion of land surrounding each focal olive orchard that was planted with olives and the proportion of land surrounding each focal vineyard that was planted with grapes. As CORINE data were not available for each year, we linearly interpolated between available years (2006, 2012, and 2018) to obtain landscape composition values for each year that pests were surveyed at each field. Second, we calculated landscape productivity surrounding each focal field. Specifically, we used Landsat 7 (2006-2017) and Landsat 8 (2018) data on Google Earth Engine to derive annual composites of the normalized difference vegetation index (NDVI). Annual mean NDVI was calculated beginning on December 15 for the olive pests and September 15 for the grape pests, reflecting the approximate harvest dates for these crops.

We chose indices of proportional land cover and productivity that weighted more heavily landscape elements that were located closer to focal fields. To do so, we first calculated land cover and productivity measurements within successive, concentric 100 meter-wide rings up to 2000 meters from each focal field. Then, we calculated a weighted average of the rings, using Gaussian functions with three different decay rates (250, 750 and 1250) to vary the relative influence of closer areas. Akaike Information Criteria (AIC) suggested the most support for a 1250 decay rate (Table S8). Thus, we present all analyses using the 1250 decay rate in the main text, but include analyses at other scales in this appendix (Table S9 & S10).

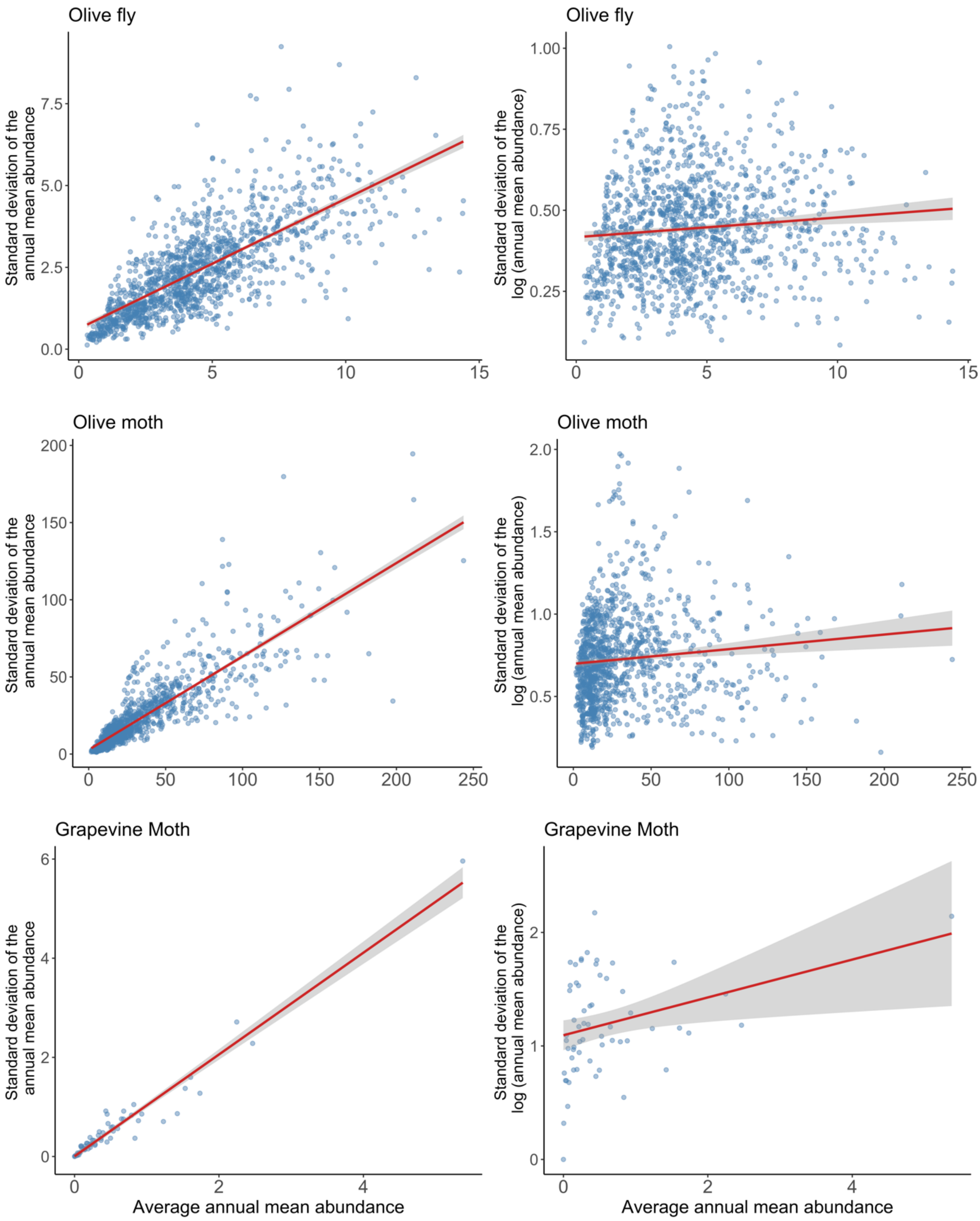

Figure S1. Relationships between average annual mean abundance and population variability for the olive fly (top panels), olive moth (middle panels), and grapevine moth (bottom panels). Strong mean-variance relationships were observed when variability was calculated as the standard deviation of annual mean abundance (left columns). However, relationships were either weak or non-existent when variability was calculated as the standard deviation of the logarithm of annual mean abundances (right columns). Red lines and gray shaded regions indicated predicted effects and 95% confidence regions from linear models.

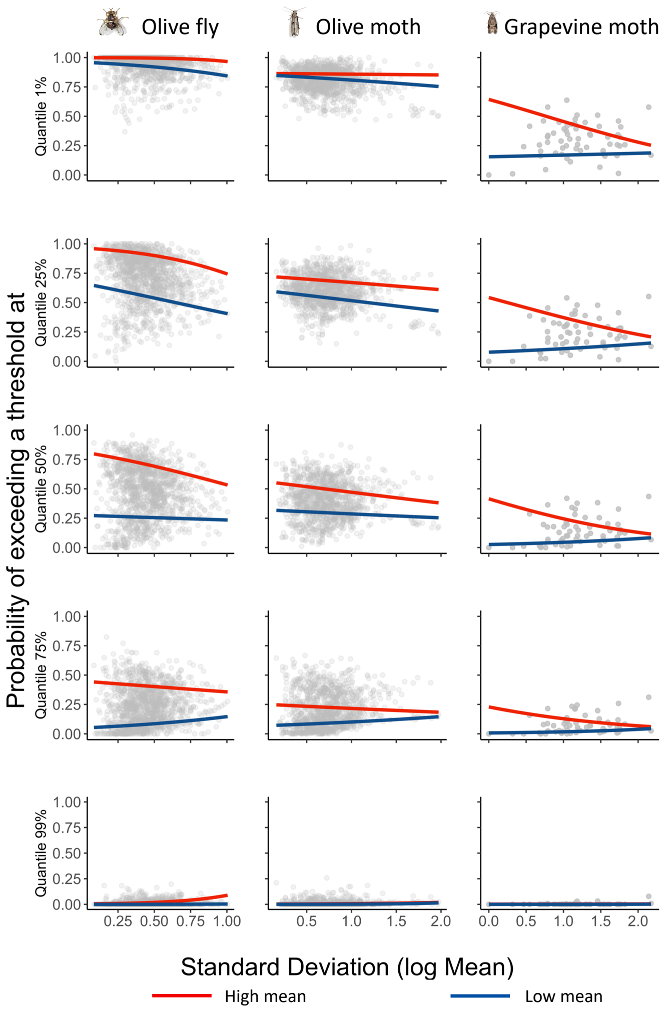

Fig. S2. Effects of pest population variability on the probability of exceeding an economic damage threshold depend on pest abundances and tolerance levels. Hypothetical pest tolerance thresholds were set at the 1%, 25%, 50%, 75%, and 99% quantiles of pest numbers trapped per week (olive fly: 0.07, 1.00, 2.70, 5.95, and 28.1 individuals/week; olive moth: 0.14, 2.57, 10.2, 34.3, and 400 individuals/week; grapevine moth 0.07, 0.21, 0.57, 1.70, and 21.7 individuals/week, respectively). Unlike Fig. 2, response variables are modeled as the fraction of weeks in which pests exceed each threshold out of all weeks across all years. At high tolerance levels (99%), variable pest populations are always more likely to exceed thresholds. At low tolerance levels (1% and 25%), pest densities are almost always above threshold levels, except when variable pest populations drop to unusually low densities. At intermediate tolerances (50% and 75%), variability in pest populations may increase, decrease, or have little effect on the risk of exceeding thresholds. Lines are predicted effects of pest variability (standard deviation of interannual log mean abundances) on the likelihood of exceeding thresholds from Generalized Linear Mixed Models (GLMMs). Red and blue lines represent fields with high mean pest densities (top 10% pest abundance quantile) and low mean pest densities (bottom 10% quantile), respectively. $N_{olive\ fly} = 1315$, $N_{olive\ moth} = 1184$, $N_{olive\ fly} = 60$.

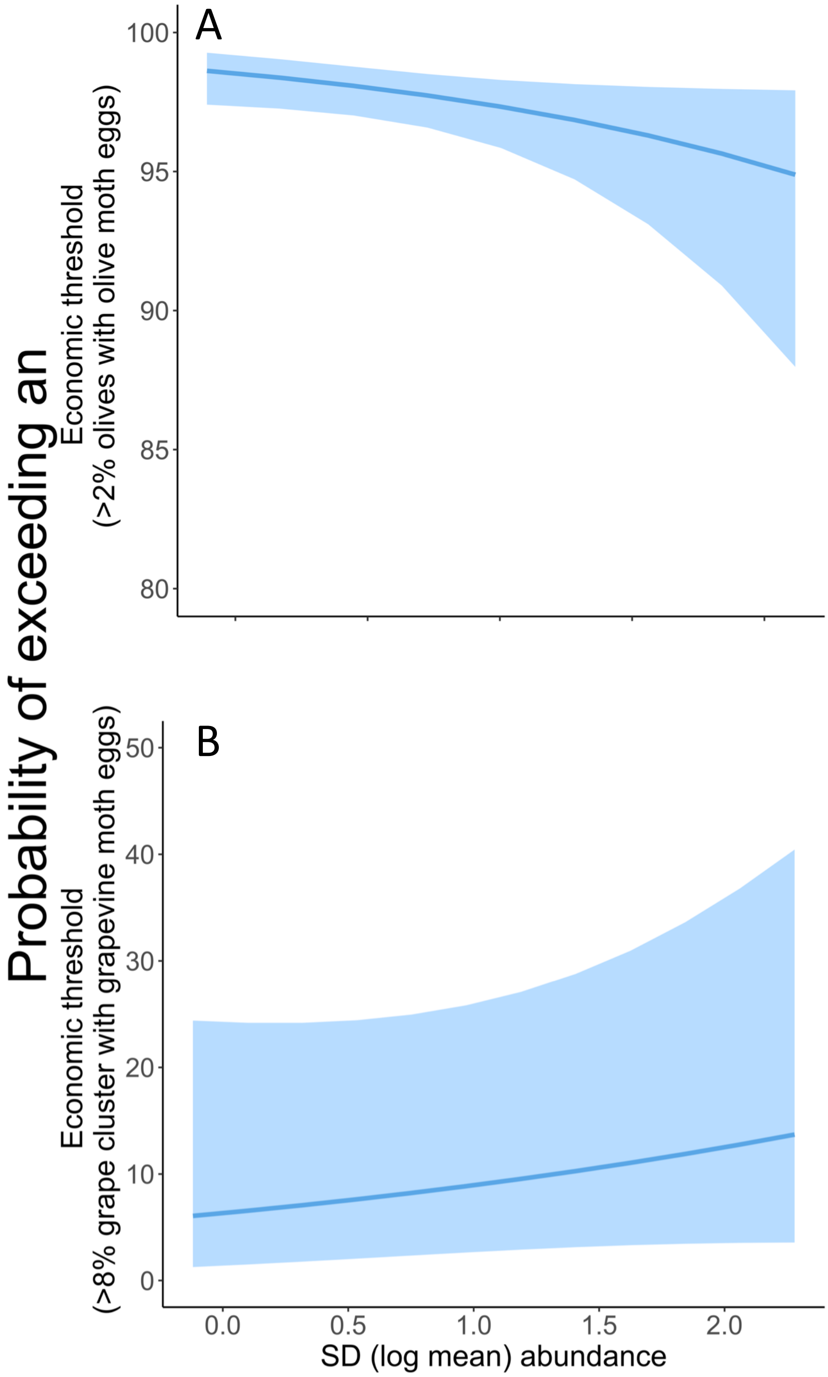

Fig. S3. Effects of olive moth and grapevine moth population variability on the probability of exceeding real-world economic thresholds. More variable olive moth populations were significantly less likely to exceed economic thresholds for spraying insecticides (**A**), whereas grapevine moth variability did not significantly influence the likelihood of exceeding economic thresholds (**B**). Blue lines and shaded regions correspond to predictions and 95% confidence regions from GLMMs ($N_{olive\ moth}$ = 1184 fields, $N_{grapevine\ moth}$= 60 fields).

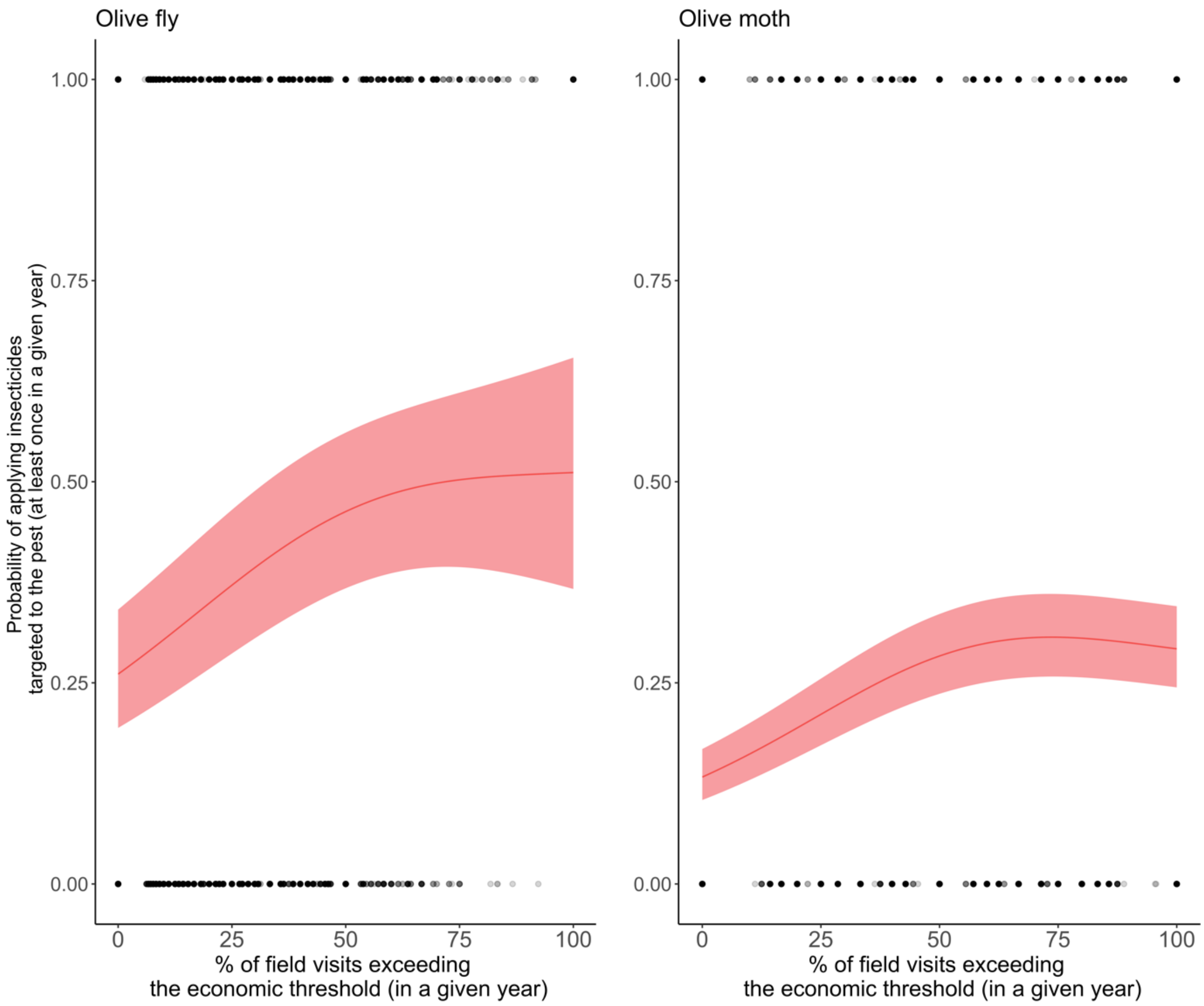

Fig. S4. Effect of the fraction of farm visits for which the economic threshold was exceeded for the olive fly (left panel) and olive moth (right panel) on the likelihood of applying insecticides targetted to each pest. Red lines and shaded regions correspond to predictions and 95% confidence regions from GAMMs. Points depict individual field-years.

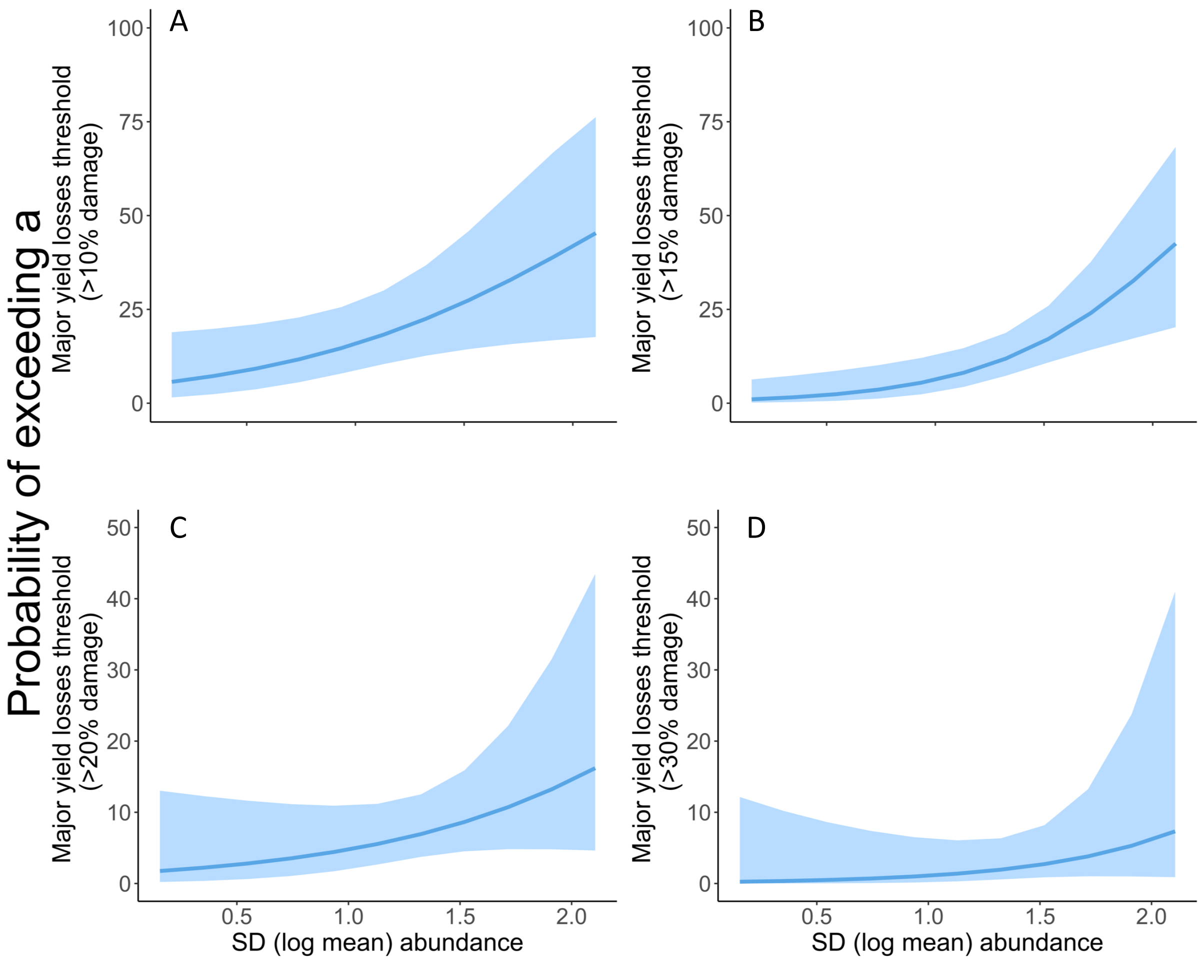

Fig. S5. Effects of grapevine moth population variability on the probability of exceeding major yield losses thresholds. Thresholds were set at 10% (**A**), 15% (**B**), 20% (**C**), and 30% yield losses (**D**). More variable populations are significantly more likely to induce major yield losses when set at lower thresholds (*i.e.,* 10% loss in panel A and 15% loss in panel B) but not at higher thresholds (*i.e.,* 20% loss in panel C and 30% loss in panel D). This is likely because very few fields ever experience such high losses from grapevine moths, decreasing our ability to model such rare events. Blue lines and shaded regions correspond to predictions and 95% confidence regions from GLMMs ($N = 39$ fields).

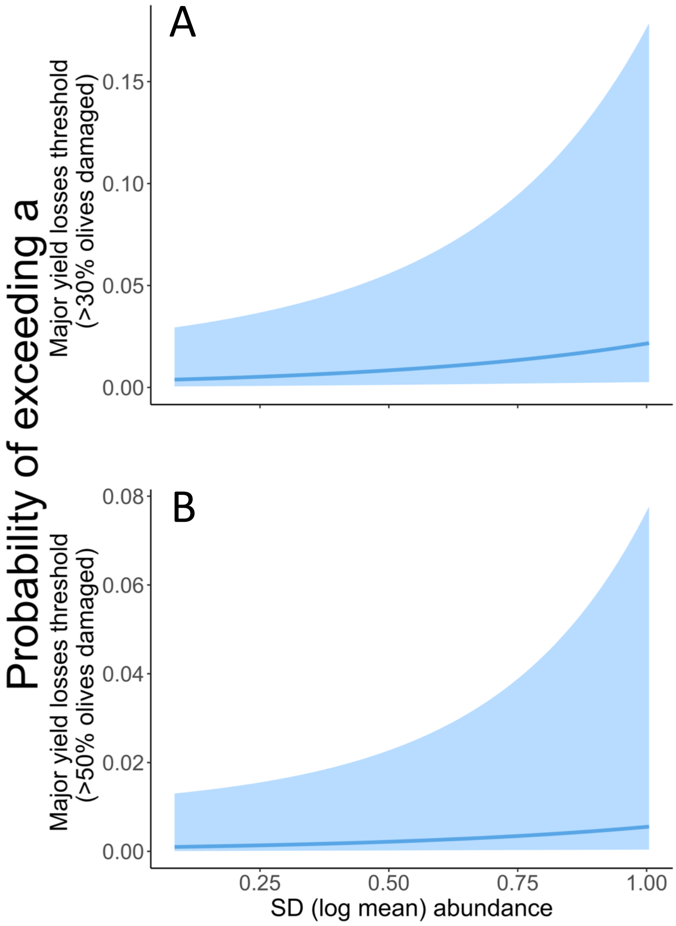

Fig. S6. Effects of olive fly population variability on the probability of exceeding major yield losses thresholds. Thresholds were set at 30% (**A**), and 50% yield losses (**B**). More variable populations are significantly more likely to induce major yield losses when set at lower thresholds (*i.e.,* 30% loss in panel A) but not at higher thresholds (*i.e.,* 50% loss in panel B). This is likely because very few fields ever experience such high losses from olive flies, decreasing our ability to model such rare events. Blue lines and shaded regions correspond to predictions and 95% confidence regions from GLMMs (N = 1270 fields).

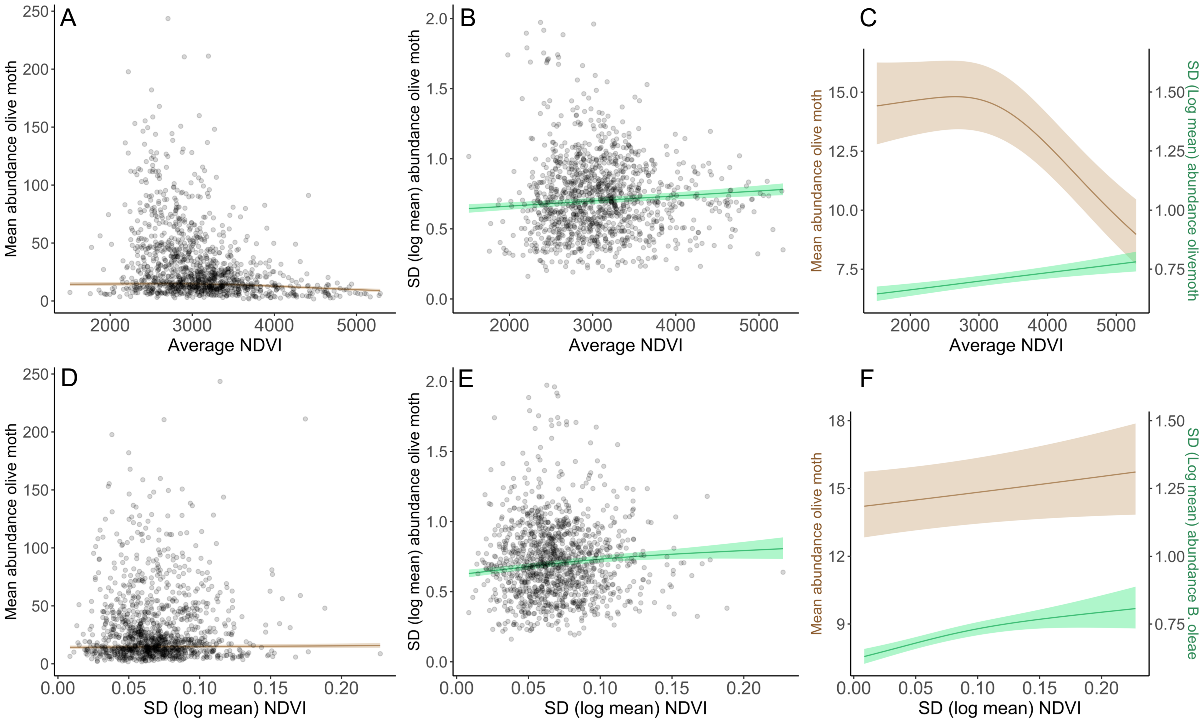

Fig. S7. Effects of landscape productivity (NDVI) and interannual variation in landscape productivity on olive moth population mean abundance and variability. Average moth abundances tend to decline on fields in more productive landscapes (**A**), whereas pest variability increases with landscape productivity (**B**). In contrast, interannual variation in landscape productivity has no effect on mean moth abundances (**D**) but increases interannual variability in moth populations (**E**). Brown lines and shaded regions represent predictions and 95% confidence intervals for mean abundance from GAMMs; green lines and shaded regions correspond to variability. Panels **C** and **F** are zoomed in to better view effects (N = 1184 fields).

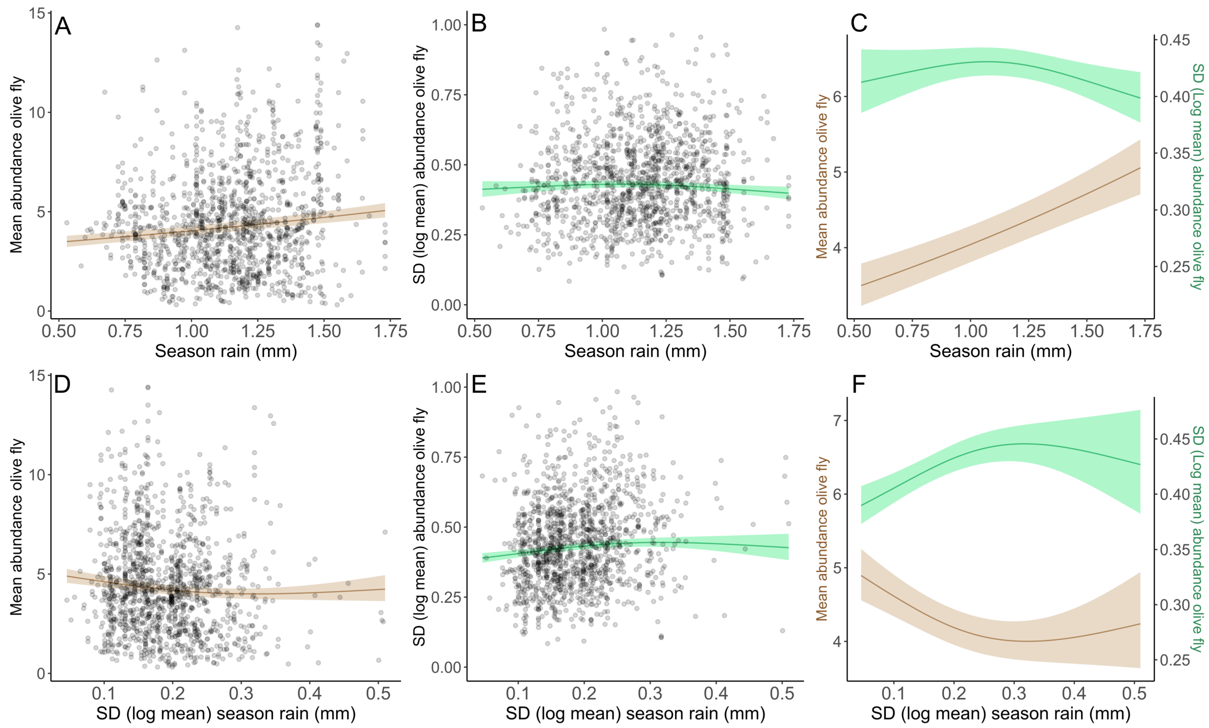

Fig. S8. Effects of growing season precipitation and interannual variation in growing season precipitation on olive fly population mean abundance and variability. Average fly abundances tend to increase on fields that experience more annual rainfall (**A**), whereas rainfall has no significant effect on pest variability (**B**). In contrast, interannual variation in rainfall significantly decreases average pest abundances (**D**) but increases interannual fly population variability (**E**). Brown lines and shaded regions represent predictions and 95% confidence intervals for mean abundance from GAMMs; green lines and shaded regions correspond to variability. Panels **C** and **F** are zoomed in to better view effects (*N* = 1315 fields).

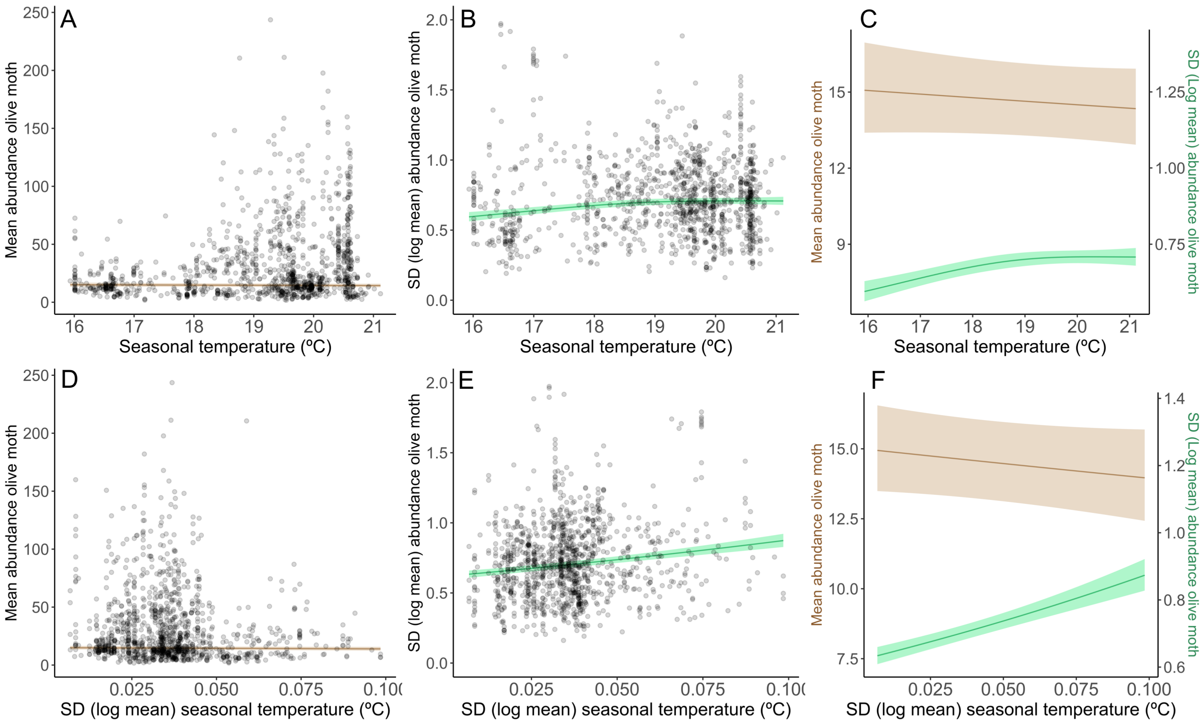

Fig. S9. Effects of growing season temperature and interannual variation in growing season temperature on olive moth population mean abundance and variability. Average moth abundances are not influenced by average growing season temperatures (**A**) or interannual variation in growing season temperatures (**D**). In contrast, moth variability increases at sites that experience hotter (**C**) or more variable (**E**) growing season temperatures. Brown lines and shaded regions represent predictions and 95% confidence intervals for mean abundance from GAMMs; green lines and shaded regions correspond to variability. Panels **C** and **F** are zoomed in to better view effects (*N* = 1184 fields).

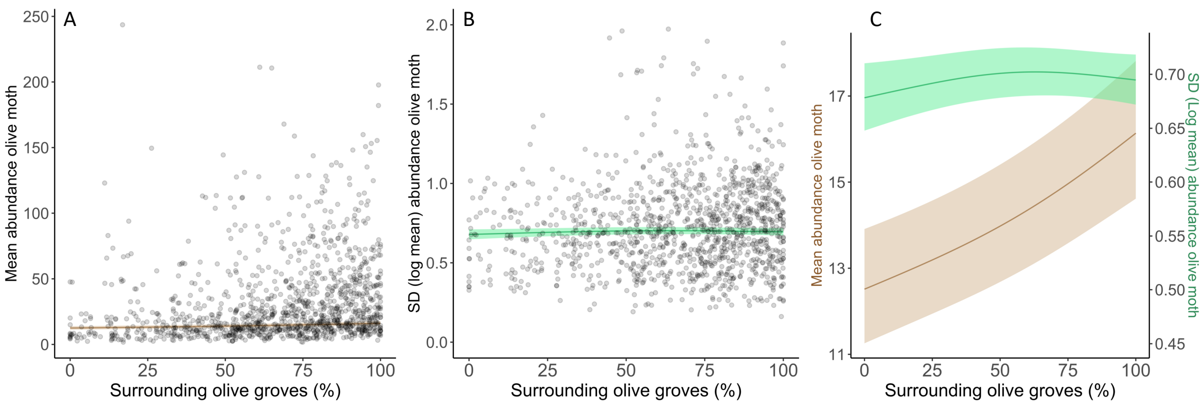

Fig. S10. **Effect of the proportion of surrounding olive groves on olive moth population mean abundance and variability**. Olive moth populations are significantly more abundant in more simplified landscapes dominated by olive orchards (**A**). In contrast, the effect of surrounding olive groves on interannual moth population variability was not significant (**B**). Brown lines and shaded regions represent predictions and 95% confidence intervals for mean abundance from GAMMs; green lines and shaded regions correspond to variability. Panel **C** is zoomed in to better view effects (N =1184 fields).

Table S1. Effects of landscape, topographic, and climate predictors on interannual pest population variability (standard deviation of the log of means) of the European grapevine moth from linear models. Landscape productivity and the fraction of surrounding vineyards are calculated at 250, 750, or 1250 decay rates (see methods). Significant values are bolded (P< 0.05).

	Decay = 1250		Decay = 750		Decay = 250	
	Estimate	Pr(>|t|)	Estimate	Pr(>|t|)	Estimate	Pr(>|t|)
Intercept	1.0778	**<0.0001**	1.0721	**<0.0001**	1.0629	**<0.0001**
Average NDVI	0.0184	0.8124	0.0340	0.6523	0.0670	0.3197
Standard Deviation NDVI (log Mean)	0.0517	0.4794	0.0674	0.3485	0.1056	0.1009
Surrounding vineyards	-0.0918	0.1313	-0.0779	0.2032	-0.0406	0.4921
Elevation	-0.0518	0.5193	-0.0532	0.5094	-0.0643	0.4208
Aspect	0.0225	0.6941	0.0214	0.7102	0.0141	0.8031
Mean abundance grapevine moth	0.2129	**0.0049**	0.2196	**0.0039**	0.2319	**0.0022**
Average Season Temperature	-0.0419	0.5536	-0.0436	0.5309	-0.0267	0.6915
Standard Deviation (log Mean) Season Temperature	0.1384	0.0786	0.1386	0.0751	0.1134	0.1403
Average Season Precipitation	0.0147	0.8221	0.0209	0.7488	0.0431	0.5095
Standard Deviation (log Mean) Season Precipitation	0.0214	0.8178	0.0191	0.8355	0.0019	0.9827

Table S2. Effects of landscape, topographic, and climate predictors, as well as random effects, on mean pest densities from GAMMs. In this case, models also include management intensity as a predictor. Landscape productivity and the fraction of surrounding focal crop are calculated at 250, 750, or 1250 decay rates (see methods). Significant values are bolded (P< 0.05).

	Olive fly			Olive moth		
	Decay = 1250	Decay = 750	Decay = 250	Decay = 1250	Decay = 750	Decay = 250
	p-value	p-value	p-value	p-value	p-value	p-value
Average NDVI	0.1443	0.2244	0.3897	**0.0009**	**0.0017**	0.0552
Standard Deviation NDVI (log Mean)	0.1726	0.2183	0.1490	0.3769	0.4304	0.4177
Surrounding olive groves (%)	**0.0118**	**0.0112**	**0.0052**	**0.0001**	**0.0002**	**0.0008**
Elevation	**<0.0001**	**<0.0001**	**<0.0001**	**0.0423**	0.0556	0.1428
Aspect	0.7820	0.7730	0.7129	0.5440	0.5464	0.4602
Management intensity	**0.0005**	**0.0005**	**0.0007**	0.2981	0.2719	0.2167
Average Season Temperature	0.1651	0.1886	0.2571	0.5585	0.5483	0.4980
Standard Deviation (log Mean) Season Temperature	0.1774	0.1918	0.2379	0.4308	0.4446	0.4471
Average Season Precipitation	**0.0005**	**0.0004**	**0.0003**	0.1895	0.1908	0.2136
Standard Deviation (log Mean) Season Precipitation	**0.0156**	**0.0181**	**0.0222**	0.0833	0.0892	0.1032
Cultivar	0.4777	0.4858	0.4953	0.4061	0.4215	0.4758
Cooperative	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Region	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
R2	0.784	0.784	0.783	0.873	0.873	0.873
Deviance explained	82.6%	82.6%	82.6%	90.3%	90.3%	90.3%

Table S3. Effects of landscape, topographic, and climate predictors, as well as random effects, on interannual pest population variability (standard deviation of the log of means) from GAMMs. In this case, models also include management intensity as a predictor. Landscape productivity and the fraction of surrounding focal crop are calculated at 250, 750, or 1250 decay rates (see methods). Significant values are bolded (P< 0.05).

	Olive fly			Olive moth		
	Decay = 1250	Decay = 750	Decay = 250	Decay = 1250	Decay = 750	Decay = 250
	p-value	p-value	p-value	p-value	p-value	p-value
Average NDVI	0.4894	0.5530	0.5887	**0.0172**	**0.0146**	**0.0200**
Standard Deviation NDVI (log Mean)	0.3318	0.3826	0.4771	**0.0006**	**0.0003**	**0.0006**
Surrounding olive groves (%)	**0.0001**	**0.0006**	**0.0253**	0.5664	0.5316	0.3355
Elevation	**<0.0001**	**<0.0001**	**<0.0001**	**0.0001**	**0.0001**	**0.0001**
Aspect	0.6682	0.6908	0.6872	0.8348	0.7340	0.7486
Management intensity	0.8150	0.8107	0.8115	0.4798	0.4697	0.4406
Mean abundance	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Average Season Temperature	**0.0441**	0.0502	0.0632	**0.0081**	**0.0079**	**0.0092**
Standard Deviation (log Mean) Season Temperature	0.5555	0.5229	0.4767	**<0.0001**	**<0.0001**	**<0.0001**
Average Season Precipitation	0.3822	0.3784	0.3790	0.1860	0.1845	0.1623
Standard Deviation (log Mean) Season Precipitation	**0.0416**	**0.0415**	**0.0458**	0.0728	0.0954	0.0912
Cultivar	0.3996	0.3924	0.3798	0.0698	0.0788	0.0977
Cooperative	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
R2	0.441	0.441	0.439	0.593	0.592	0.591
Deviance explained	50.8%	50.8%	50.7%	66.0%	65.9%	65.8%

Table S4. Effects of interannual pest population variability (standard deviation of the log of mean densities) and the pest abundance (across years) on the likelihood of pests exceeding hypothetical density thresholds set at 1%, 25%, 50%, 75%, and 99% abundance quantiles. Estimates and P values are obtained from GLMMs (see methods).

		Olive fly		Olive moth		Grapevine moth	
		Estimate	Pr(>|z|)	Estimate	Pr(>|z|)	Estimate	Pr(>|z|)
Quantile 1%	Intercept	8.2317	<0.0001	16.9454	0.0008	5.5549	<0.0001
	Mean abundance	0.6143	0.0069	1.8618	0.6644	7.8805	<0.0001
	SD (log mean) abundance	-0.1639	0.1786	-1.6389	0.0563	-2.2553	<0.0001
	Interaction mean abundance & SD (log mean) abundance	-0.2289	0.0572	-0.3101	0.8390	-3.3197	<0.0001
Quantile 25%	Intercept	4.4312	<0.0001	11.6300	<0.0001	4.3856	<0.0001
	Mean abundance	2.0701	<0.0001	9.8815	<0.0001	6.9954	<0.0001
	SD (log mean) abundance	-0.8943	<0.0001	-2.8654	<0.0001	-1.9786	<0.0001
	Interaction mean abundance & SD (log mean) abundance	-0.5657	<0.0001	-2.1553	<0.0001	-2.9484	<0.0001
Quantile 50%	Intercept	3.2971	<0.0001	7.1739	<0.0001	2.2657	<0.0001
	Mean abundance	2.8585	<0.0001	7.5773	<0.0001	4.9378	<0.0001
	SD (log mean) abundance	-1.1331	<0.0001	-2.1279	<0.0001	-1.1122	<0.0001
	Interaction mean abundance & SD (log mean) abundance	-0.8176	<0.0001	-1.7270	<0.0001	-2.1166	<0.0001
Quantile 75%	Intercept	0.9763	<0.0001	2.2174	<0.0001	0.0618	0.8614
	Mean abundance	2.0470	<0.0001	3.5741	<0.0001	2.1633	<0.0001
	SD (log mean) abundance	-0.4465	<0.0001	-0.8414	<0.0001	-0.2762	0.0410
	Interaction mean abundance & SD (log mean) abundance	-0.7042	<0.0001	-0.9776	<0.0001	-0.8810	<0.0001
Quantile 99%	Intercept	-3.9896	<0.0001	-3.7627	<0.0001	-5.5315	<0.0001
	Mean abundance	1.5165	<0.0001	1.4858	<0.0001	2.3988	<0.0001
	SD (log mean) abundance	0.5857	<0.0001	0.5155	<0.0001	0.9490	0.1822
	Interaction mean abundance & SD (log mean) abundance	-0.1296	0.0143	-0.2857	<0.0001	-0.8658	0.0019

Table S5. Effects of interannual pest population variability (standard deviation of the log of mean densities) on the likelihood of pests exceeding established economic thresholds, crop quality thresholds (olive fly only), or major crop losses thresholds (20% crop loss for olive fly; 10% crop loss for grapevine moth). Estimates and P values are obtained from GLMMs (see methods).

	Economic		Quality		Major crop losses	
	Estimate	p-value	Estimate	p-value	Estimate	p-value
Olive fly	0.0395	0.3047	0.1952	0.0156	0.2527	0.0276
Olive moth	-0.1688	0.0441				
Grapevine moth	0.1633	0.3091			0.5240	0.0302

Table S6. Effects of interannual pest population variability (standard deviation of the log of mean densities) on the likelihood of pests exceeding major crop losses thresholds set at 15%, 20%, 30% and 50% of crop damage thresholds. Threshold of 20% of crop damage for the olive fly is reported in Table S2. Thresholds of 15% crop damage for the olive fly and 50% crop damage for the grapevine moth were not calculated. Estimates and P values are obtained from GLMMs (see methods).

	15% damage		20% damage		30% damage		50% damage	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Olive fly					0.2985	0.0416	0.2964	0.131
Grapevine moth	0.8489	0.0022	0.4762	0.1500	0.6910	0.2340		

Table S7. Effects of landscape, topographic, and climate predictors, as well as random effects, on mean pest densities and interannual pest population variability (standard deviation of the log of means) from GAMMs. Bolded numbers indicate significant effects. Landscape productivity and the fraction of surrounding focal crop were calculated using a decay rate of 1250 (see methods).

	Olive Fly		Olive Moth	
	Mean abundance	SD (log mean) abundance	Mean abundance	SD (log mean) abundance
	p-value	p-value	p-value	p-value
Average NDVI	0.1828	0.4723	**0.0008**	**0.0128**
Standard Deviation NDVI (log Mean)	0.1463	0.3206	0.3807	**0.0005**
Surrounding olive groves (%)	**0.0072**	**0.0001**	**0.0001**	0.5650
Elevation	**<0.0001**	**<0.0001**	**0.0460**	**0.0001**
Aspect	0.8448	0.6665	0.5519	0.8367
Mean abundance		**<0.0001**		**<0.0001**
Average Season Temperature	0.1631	**0.0439**	0.6413	**0.0104**
Standard Deviation (log Mean) Season Temperature	0.1941	0.5713	0.4893	**<0.0001**
Average Season Precipitation	**0.0002**	0.3751	0.1818	0.1961
Standard Deviation (log Mean) Season Precipitation	**0.0140**	**0.0422**	0.0777	0.0662
Cultivar	0.4740	0.4282	0.3085	0.0782
Cooperative	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Region	**<0.0001**		**<0.0001**	
R^2	0.780	0.442	0.873	0.594
Deviance explained	82.3%	50.8%	90.3%	66.1%

Table S8. AIC values of models computed with landscape productivity and fraction of surrounding focal crop calculated with different decay rates (see methods). Lowest values of AIC within a difference of two units are bolded.

	AIC			
	Olive fly		Olive moth	
Decay rate	Mean	SD (log mean)	Mean	SD (log mean)
1250	901.5959	**570.7019**	**1009.589**	237.4677
750	902.7039	572.9191	**1009.615**	**234.9597**
250	**898.4987**	579.2334	1012.509	**234.6733**

Table S9. Effects of landscape, topographic, and climate predictors, as well as random effects, on mean pest densities from GAMMs. Landscape productivity and fraction of surrounding focal crop were calculated at decay rates of either 250 or 750 m (see methods). Significant values are bolded (P< 0.05).

	Olive fly		Olive moth	
	Decay = 750	Decay = 250	Decay = 750	Decay = 250
	p-value	p-value	p-value	p-value
Average NDVI	0.2719	0.3936	**0.0016**	0.0549
Standard Deviation NDVI (log Mean)	0.1887	0.1314	0.4373	0.4321
Surrounding olive groves (%)	**0.0088**	**0.0017**	**0.0002**	**0.0007**
Elevation	**<0.0001**	**<0.0001**	**0.0622**	0.1567
Aspect	0.8321	0.7833	0.5542	0.4733
Average Season Temperature	0.1839	0.2376	0.6351	0.5940
Standard Deviation (log Mean) Season Temperature	0.2081	0.2552	0.5078	0.5181
Average Season Precipitation	**0.0002**	**0.0001**	0.1822	0.1998
Standard Deviation (log Mean) Season Precipitation	**0.0160**	**0.0181**	0.0824	0.0864
Cultivar	0.4759	0.5008	0.3249	0.3943
Cooperative	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Region	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
R2	0.780	0.780	0.874	0.873
Deviance explained	82.2%	82.2%	90.3%	90.3%

Table S10. Effects of landscape, topographic, and climate predictors, as well as random effects, on interannual pest population variability (standard deviation of the log of means) from GAMMs. In this case, landscape productivity and the fraction of surrounding focal crop are calculated at decay rates of either 250 or 750 (see methods). Significant values are bolded (P< 0.05).

	Olive fly		Olive moth	
	Decay = 750	Decay = 250	Decay = 750	Decay = 250
	p-value	p-value	p-value	p-value
Average NDVI	0.5364	0.5762	**0.0109**	**0.0175**
Standard Deviation NDVI (log Mean)	0.3716	0.4651	**0.0003**	**0.0005**
Surrounding olive groves (%)	**0.0006**	**0.0258**	0.5428	0.3486
Elevation	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Aspect	0.6890	0.6852	0.7349	0.7498
Mean abundance	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Average Season Temperature	0.0501	0.0634	**0.0103**	**0.0120**
Standard Deviation (log Mean) Season Temperature	0.5384	0.4913	**<0.0001**	**<0.0001**
Average Season Precipitation	0.3711	0.3717	0.1955	0.1723
Standard Deviation (log Mean) Season Precipitation	**0.0421**	**0.0463**	0.0868	0.0827
Cultivar	0.4244	0.4097	0.0878	0.1076
Cooperative	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
R2	0.441	0.439	0.593	0.592
Deviance explained	50.8%	50.7%	66.0%	65.9%