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Honeybee spillover reshuffles pollinator diets and affects plant reproductive success

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Keywords: Agro ecosystems, floral resources, interaction rewiring, mass-flowering crop, orange grove, plant-pollinator networks, pollen tube, seed set, resource pulse

Supplementary information

Supplementary Table 1. List of pollinator species found within woodlands surveyed

Ammobates (Euphileremus) muticus Spinola, 1843
Ammobates (Ammobates) punctatus (Fabricius, 1804)
Andrena (Ptilandrena) angustior impressa Warncke, 1967
Andrena (Simandrena) antigana Pérez, 1895
Andrena (Chlorandrena) cinerea Brullé, 1832
Andrena flavipes Panzer, 1799
Andrena (Melandrena) hispania Warncke, 1967
Andrena (Chlorandrena) humilis Imho-, 1832
Andrena (Holandrena) labialis (Kirby, 1802)
Andrena marginata Fabricius,1776
Andrena (Melandrena) nigroaenea Dours, 1872
Andrena (Notandrena) nitidiuscula Schenck, 1853
Andrena (Taeniandrena) ovatula (Kirby, 1802)
Andrena (Chlorandrena) rhyssonota Pérez, 1895
Andrena sp1
Andrena sp2
Andrena sp3
Andrena sp4
Andrena sp5
Andrena sp6
Andrena sp7
Andrena sp8
Andrena sp9
Andrena sp10
Andrena sp11
Andrena sp12
Andrena sp13
Andrena sp14
Andrena sp15
Andrena sp16
Andrena sp17
Andrena sp18
Andrena sp19
Andrena (Micrandrena) spreta Pérez, 1895
Andrena tenuistriata Pérez
Andrena (Melandrena) thoracica (Fabricius, 1775)
Andrena(Chlorandrena) sp1
Andrena (Truncandrena) villipes Pérez, 1895
Anthidiellum strigatum Panzer, 1805
Anthidium manicatum Linnaeus 1758

Anthidium septemdentatum Latreille, 1809
Anthidium sp1
Anthidium strigatum Panzer, 1805
Anthophora (Pyganthophora) atroalba Lepeletier, 1841
Anthophora bimaculata Panzer, 1798
Anthophora (Lophanthophora) dispar (Lepeletier, 1841)
Anthophora (Anthophora) plumipes (Pallas, 1772)
Anthophora sp1
Anthophora sp2
Apis (Apis) mellifera Linnaeus, 1758
Bombus (Bombus) terrestris (Linnaeus, 1758)
Ceratina (Euceratina) chalybea Chevrier, 1872
Ceratina (Ceratina) cucurbitina (Rossi, 1792)
Ceratina (Euceratina) cyanea (Kirby, 1802)
Ceratina (Euceratina) dentiventris Gerstäcker, 1869
Ceratina (Euceratina) mocsaryi Friese, 1896
Ceratina sp1
Ceratina sp2
Ceratina sp3
Ceratina sp4
Ceratina sp5
Ceratina sp6
Ceratina sp7
Ceratina sp8
Ceratina sp9
Ceratina sp10
Ceratina sp11
Ceratina sp12
Ceriana vespiforme (Latreille, 1804)
Chalicodoma ericetorum (Lepeletier 1841)
Megachile (Chalicodoma) sicula Rossi, 1792
Chalicodoma sicula hiendlmayri (Friese, 1896)
Cheilosia latifrons (Zetterstedt, 1843)
Chelostoma florisomne (Linnaeus, 1758)
Chrysididae sp1
Chrysididae sp2
Chrysididae sp3
Chrysididae sp4
Chrysididae sp5
Colletes acutus Pérez, 1903
Colletes foveolaris Pérez, 1903
Colletes mlokossewiczi Radoszkowski, 1891
Colletes nigricans Gistel, 1857

Crabronidae(Oxybelus) sp1
Dasypoda albimana Pérez, 1905
Dasypoda cingulata Erichson 1835
Dasypoda crassicornis Friese, 1896
Dufourea (Dufourea) trautmanni Dusmet, 1935
Episyrphus balteatus (De Geer, 1776)
Eristalinus aeneus (Scopoli, 1763)
Eristalinus taeniops (Wiedemann, 1818)
Eristalis arbustorum (Linnaeus, 1758)
Eristalis similis (Fallén, 1817)
Eristalis sp1
Eristalis sp2
Eristalis tenax (Linnaeus, 1758)
Eucera alternans (Brullé, 1832)
Eucera (Hetereucera) barbiventris Pérez, 1902
Eucera (Eucera) chrysopyga Pérez, 1879
Eucera (Stilbeucera) clypeata Erichson, 1835
Eucera (Hetereucera) collaris Dours, 1873
Eucera (Hetereucera) elongatula Vachal, 1907
Eucera (Hetereucera) hispana Lepeletier, 1841
Eucera (Hetereucera) notata Lepeletier, 1841
Eucera sp1
Eucera sp2
Eucera sp3
Eucera sp4
Eucera sp5
Eucera sp6
Eucera sp7
Eucera sp8
Eucera sp9
Eucera sp10
Eucera sp11
Eucera sp12
Eucera sp13
Eucera sp14
Eucera sp15
Eucera sp16
Eupeodes sp1
Flavipanurgus venustus (Erichson, 1835)
Halictus (Halictus) fulvipes (Klug, 1817)
Halictus (Seladonia) gemmeus Dours, 1872
Halictus (Vestitohalictus) pollinosus Sichel, 1860
Halictus (Halictus) scabiosae (Rossi, 1790)

Halictus (Seladonia) smaragdulus Vachal, 1895
Halictus sp1
Halictus (Seladonia) subauratus (Rossi, 1792)
Hoplitis(Hoplitis) adunca (Panzer, 1798)
Hoplitis(Hoplitis) benoisti (Alfken, 1935)
Hoplitis(Hoplitis) crenulata (Morawitz, 1871)
Hoplitis papaveris (Latreille, 1799)
Hoplitis sp1
Hoplitis (Anthocopa) antigae (Pérez, 1895)
Hoplitis (Anthocopa) scutellaris (Morawitz, 1868)
Hylaeus pictus (Smith, 1853)
Hylaeus variegatus (Fabricius, 1798)
Lasioglossum (Lasioglossum) albocinctum (Lucas, 1849)
Lasioglossum callizonium (Pérez, 1896)
Lasioglossum (Evylaeus) capitalis (Pérez, 1903)
Lasioglossum (Lasioglossum) costulatum (Kriechbaumer, 1873)
Lasioglossum (Lasioglossum) discum (Smith, 1853)
Lasioglossum (Evylaeus) immunitum (Vachal, 1895)
Lasioglossum sp1
Lasioglossum (Evylaeus) interruptum (Panzer, 1798)
Lasioglossum (Lasioglossum) lativentre (Schenck, 1853)
Lasioglossum (Evylaeus) immunitum (Vachal, 1895)
Lasioglossum (Lasioglossum) leucozonium Ebmer, 1976
Lasioglossum (Evylaeus) malachurum (Kirby, 1802)
Lasioglossum (Evylaeus) mediterraneum (Blüthgen, 1926)
Lasioglossum (Evylaeus) pauperatum (Brullé, 1832)
Lasioglossum (Evylaeus) pauxillum (Schenck, 1853)
Lasioglossum (Evylaeus) pygmaeum (Schenck, 1853)
Lasioglossum (Lasioglossum) sexnotatum (Kirby, 1802)
Lasioglossum sp2
Lasioglossum sp3
Lasioglossum sp4
Lasioglossum sp5
Lasioglossum sp6
Lasioglossum sp7
Lasioglossum sp8
Lasioglossum sp9
Lasioglossum sp10
Lasioglossum sp11
Lasioglossum (Evylaeus) sphecodimorphum (Vachal, 1892)
Lasioglossum (Evylaeus) villosulum (Kirby, 1802)
Megachile(Neoeutricharaea) deceptoria Pérez, 1890

Megachile opacifrons Pérez, 1897
Megachile (Eutricharaea) pilidens Alfken, 1924
Megachile sp1
Megachilidae sp2
Megascolia maculata (Fabricius, 1775)
Melitturga (Petrusianna) caudata Pérez, 1879
Merodon elegans Hurkmans, 1993
Merodon pumilus Macquart, 1849
Merodon sp1
Myathropa florea (Linnaeus 1758)
Nomada agrestis Fabricius, 1787
Nomada melathoracica Imhoff, 1834
Nomada nobilis Herrich-Schäffer, 1839
Nomada sp1
Nomada sp2
Nomada sp3
Nomada sp4
Osmia (Helicosmia) aurulenta (Panzer, 1799)
Osmia (Helicosmia) caerulescens (Linnaeus, 1758)
Osmia (Helicosmia) latreillei Spinola, 1806
Osmia ligurica Morawitz, 1868
Osmia (Osmia) rufa (Linnaeus, 1758)
Osmia sp1
Osmia (Helicosmia) signata Erichson, 1835
Osmia sp2
Osmia (Pyrosmia) submicans (Morawitz, 1870)
Osmia (Metallinella) brevicornis (Fabricius, 1798)
Oxybelus mucronatus (Fabricius, 1793)
Oxybelus quattuordecimnotatus Jurine, 1807
Panurginus albopilosus (Lucas, 1846)
Panurgus (Euryvalvus) banksianus (Kirby 1802)
Panurgus (Panurgus) calcaratus (Scopoli 1763)
Panurgus (Panurgus) dargius Warncke, 1972
Panurgus (Panurgus) cephalotes *Latreille, 1811*
Panurgus (Panurgus) perezi Saunders, 1882
Panurgus sp1
Panurgus sp2
Panurgus sp3
Platynochaetus setosus Fabricius, 1794
Protosmia capitata (Schletterer, 1889)
Pseudapis (Nomiapis) bispinosa (Brullé, 1832)
Rhodanthidium(Rhodanthidium) sticticum (Fabricius, 1793)
Scaeva selenitica (Meigen, 1822)

Scolidae sp1
Sphaerophoria scripta (Linnaeus, 1758)
Syritta pipiens (Linnaeus, 1758)
Syrphidae sp1
Syrphidae sp2
Syrphidae sp3
Syrphidae sp4
Syrphidae sp5
Syrphidae sp6
Syrphidae sp7
Syrphidae sp8
Syrphidae sp9
Syrphidae sp10
Syrphidae sp11
Syrphidae sp12
Syrphidae sp13
Syrphidae sp14
Syrphidae sp15
Syrphidae sp16
Syrphidae sp17
Syrphidae sp18
Syrphidae sp19
Syrphus vitripennis Meigen, 1822
Systropha planidens grandimargo Pérez, 1905
Thyreus histrionicus (Illiger, 1806)
Volucella zonaria (Poda, 1761)
Xanthogramma marginale (Loew, 1854)
Xylocopa (Rhysoxylocopa) cantabrita Lepeletier, 1841
Xylocopa (Xylocopa) violacea (Linnaeus, 1758)

Supplementary Table 2. List of plant species found in the surveyed woodlands

Andryala integrifolia L.
Andryala ragusina L.
Andryala sp1
Andryala sp2
Asphodelus aestivus Brot.
Campanula lusitanica L. in Loefl.
Campanula rapunculus L.
Centaurium erythraea Rafn
Centranthus calcitrapae (L.) Dufr.
Cistus albidus L.
Cistus crispus L.
Cistus ladanifer L.
Cistus libanotis L.
Cistus monspeliensis L.
Cistus salviifolius L.
Convolvulus althaeoides L.
Crataegus monogyna Jacq.
Crepis capillaris (L.) Wallr.
Cytisus scoparius (L.) Link
Echium plantagineum L.
Elaeoselinum foetidum (L.) Boiss.
Erodium sp1
Erodium/Geranium sp1
Galactites tomentosa Moench
Genista hirsuta Vahl
Genista sp1
Genista triacanthos Brot.
Geranium sp1
Gladiolus illyricus W.D.J.Koch
Halimium calycinum (L.) K.Koch
Halimium halimifolium L. Willk.
Helichrysum picardii Boiss. & Reuter in Boiss.
Jasione montana L.
Lavandula stoechas Lam.
Leontodon longirostris (Finch & P.D.Sell) Talavera
Linaria viscosa (L.) Chaz
Osyris lanceolata Hochst. & Steud.
Oxalis pes-caprae L.
Parentucellia viscosa (L.) Caruel
Phlomis purpurea L.
Pistacia lentiscus L.

Plantago coronopus L.
Pulicaria odora (L.) Reichenb.
Quercus coccifera L.
Quercus ilex L.
Quercus suber L.
Retama sphaerocarpa (L.) Boiss.
Rosmarinus officinalis L.
Ruta montana L.
Scabiosa columbaria L.
Sesamoides interrupta (Boreau) G. López
Silene sp1
Sonchus oleraceus L.
Teucrium fruticans L.
Thapsia villosa L.
Tolpis barbata (L.) Gaertner
Tuberaria guttata (L.) Raf.
Tuberaria sp1
Vicia lutea L.

Supplementary Table 3. Percentage of interactions that involve honeybees as opposed to other pollinators at each at the landscape type, and period combinations.

	High grove cover		**Low grove cover**	
	During	**After**	**During**	**After**
Honeybees	68.65 ± 14.09	72.93 ± 9.80	52.40 ± 25.71	38.66 ± 15.23
Other pollinators	31.34 ± 14.09	27.07 ± 9.80	47.60 ± 25.71	66.17 ± 19.64

Supplementary Table 4. Estimates ± Standard errors of spatial and temporal variables affecting apparent competition (Mūller's index) included in the averaged models (for all models with ΔAIC values < 6). Results shown are for analyses using binomial error structure where values were transformed to 0 if a pollinator species shared no resources with honeybees and 1 otherwise). Fixed factors included were Period (during or after), Landscape type (low or high grove cover), Year (2011 or 2012). In all cases 'during' and 'low' were used as the reference categories for the variables period and landscape type. Bold numbers indicate significant variables.

Apparent competition: Binomial	**Estimate ± S.E.**
(Intercept)	**1.16 ± 0.28**
Period	-0.08 ± 0.34
Landscape type	-1.67 ± 1.28
Honeybee abundance	-0.05 ± 0.18
Year	**1.07 ± 0.22**
Flower cover	-0.18 ± 0.18
Period x Landscape type	**4.99 ± 1.62**
Period x Honeybee abundance	0.84 ± 0.52
Landscape type x Honeybee abundance	-0.01 ± 1.40
Period x Landscape type x Honeybee abundance	**4.40 ± 1.85**

Supplementary Table 5. Estimates ± Standard errors of spatial and temporal variables affecting link density a) for the whole pollinator community and b) for the subset of native species only included in the averaged models (for all models with ΔAIC values < 6). Fixed factors included were Period (during or after), Landscape type (low or high orange grove cover), Year (2011 or 2012). In all cases 'during' and 'low' were used as the reference categories for the variables period and landscape type. Honeybee abundance was included as a covariate. Bold numbers indicate significant variables.

a) Link density	**Estimate ± S.E.**
(Intercept)	**73.87 ± 152.9**
Period	**0.29 ± 0.09**
Landscape type	**0.27 ± 0.13**
Honeybee abundance	**-0.20 ± 0.06**
Pollinator species diversity	**0.31 ± 0.08**
Year	-0.13 ± 0.09
Period x Pollinator species diversity	-0.14 ± 0.11
Period x Honeybee abundance	-0.16 ± 0.14

b) Link density (native species only)	**Estimate ± S.E.**
(Intercept)	**1.31 ± 0.32**
Period	-0.02 ± 0.19
Landscape type	-0.36 ± 0.29
Honeybee abundance	**-0.01 ± 0.00**
Pollinator species diversity	**0.11 ± 0.01**
Year	**-0.41 ± 0.14**
Flower cover	-0.03 ± 0.06
Period x Landscape type	0.20 ± 0.44
Period x Honeybee abundance	0.00 ± 0.00
Landscape type x Honeybee abundance	0.04 ± 0.02
Period x Landscape type x Honeybee abundance	-0.02 ± 0.03

Supplementary Table 6. Estimates ± Standard errors of variables included in the full model for the effect of landscape type and honeybee abundance on pollen limitation for two wild plant species a) *Cistus salvifolius* and b) *Cistus crispus*. In both cases 'low' was used as the reference category for the variable landscape type. Bold numbers indicate significant variables. Pollen limitation is calculated as 1-(number of seeds produced in control flowers/ number of seeds produced in flowers supplemented with pollen).

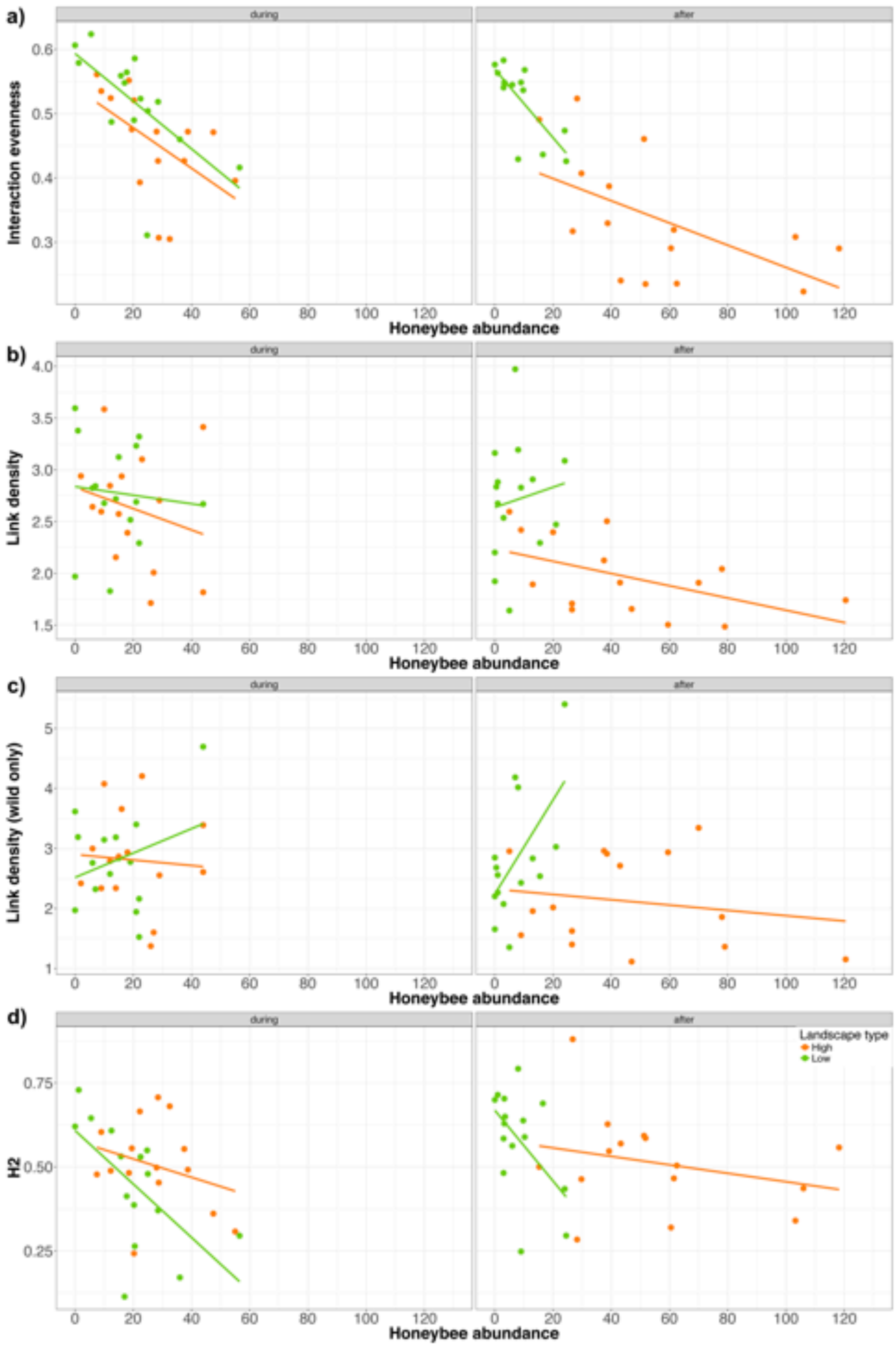
a) *C. salvifolius*	**Estimate ± S.E.**
(Intercept)	**0.53 ± 0.10**
Landscape type	**-0.36 ± 0.15**
Honeybee abundance	-0.00 ± 0.00
Landscape type x Honeybee abundance	0.00 ± 0.00
b) *C. crispus*	
(Intercept)	**0.22 ± 0.08**
Landscape type	0.03 ± 0.11
Honeybee abundance	-0.00 ± 0.00
Landscape type x Honeybee abundance	0.00 ± 0.00

Supplementary Table 7. Confidence intervals for variables included in the model evaluating the effect of honeybee visit number on pollen tube numbers for *C. crispus*. Bold numbers indicate significant variables. We show different fits using quantile regression given that visual inspection suggested a non-constant variance.

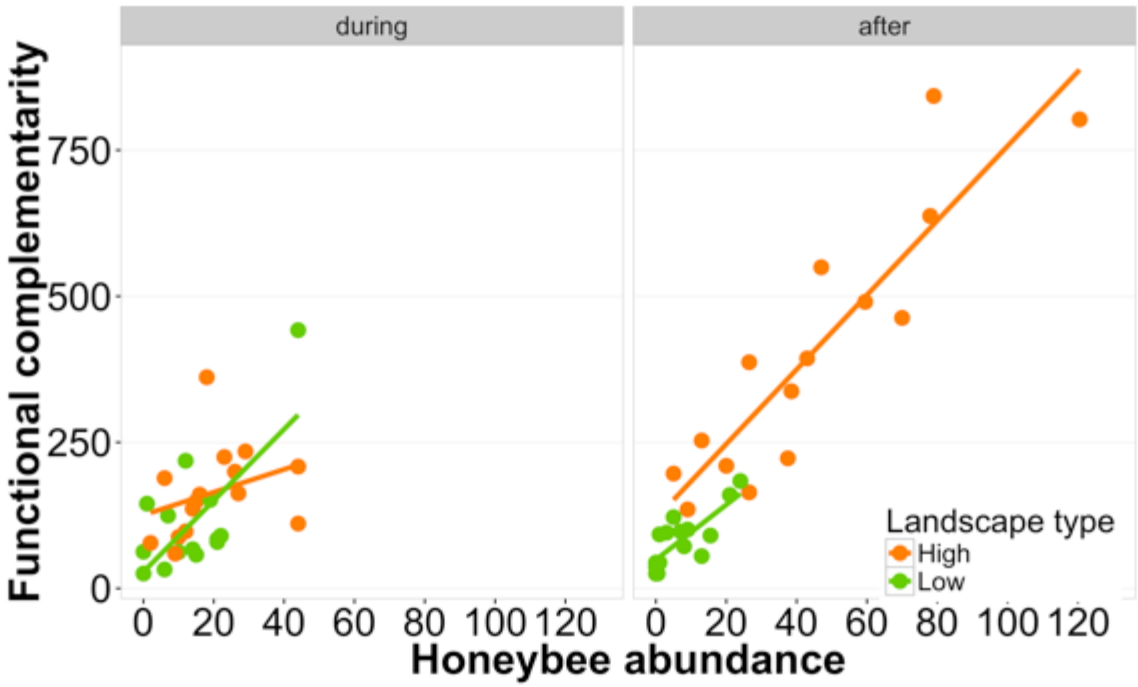
Pollen tubes *C. crispus*	**Confidence interval**
Quantile = 0.1	
(Intercept)	**5.98, 9.90**
Honeybee visits	-0.27, 0.26
Quantile = 0.25	
(Intercept)	**8.41, 20.20**
Honeybee visits	-0.44, 0.54
Quantile = 0.5	
(Intercept)	**19.86, 42.99**
Honeybee visits	-1.16, 0.25
Quantile = 0.75	
(Intercept)	**42.65, 58.16**
Honeybee visits	**-1.35, -0.72**
Quantile = 0.90	
(Intercept)	**57.06, 82.96**
Honeybee visits	**-2.02, -0.07**

Supplementary Table 8. Estimates ± Standard errors of variables included in the full model for the effect of landscape type and honeybee abundance on fruit set for two wild plant species a) *Cistus salvifolius* and b) *Cistus crispus*. In both cases 'low' was used as the reference category for the variable landscape type. Bold numbers indicate significant variables.

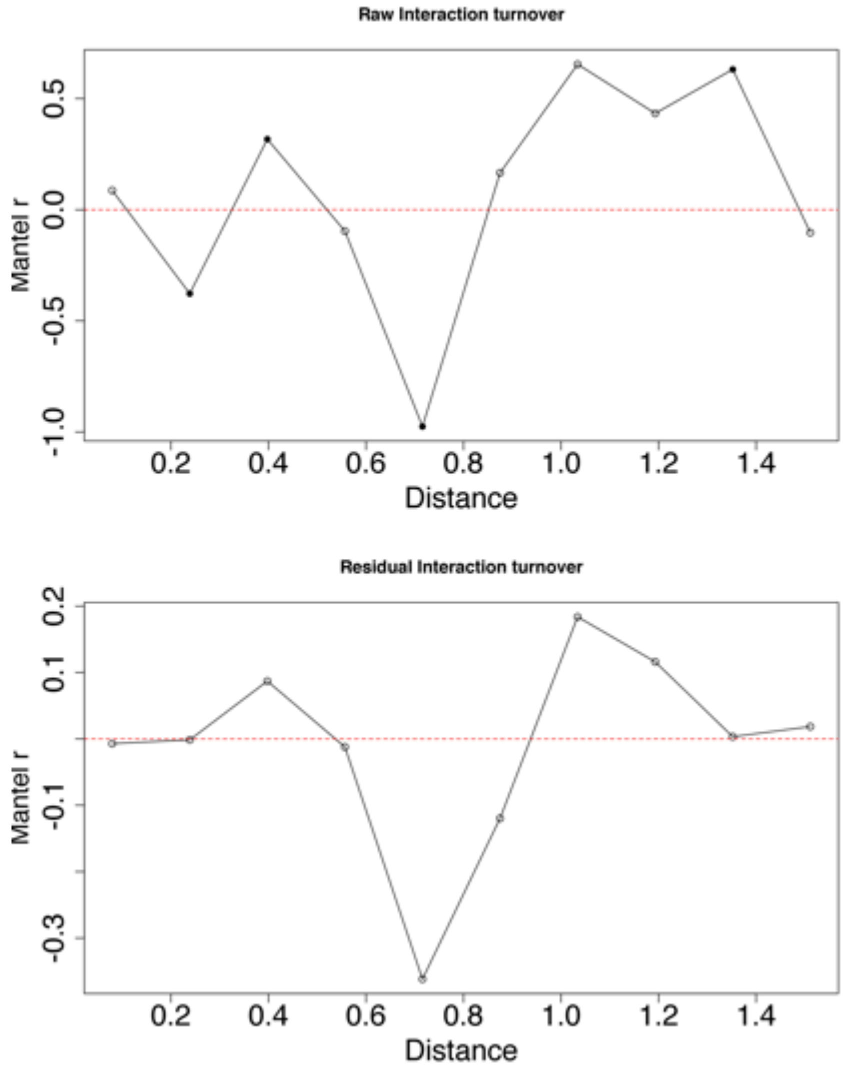
a) *C. salvifolius*	**Estimate ± S.E.**
(Intercept)	-0.58 ± 0.40
Landscape type	0.00 ± 0.49
Honeybee abundance	-0.00 ± 0.01
Landscape type x Honeybee abundance	0.00 ± 0.03
b) *C. crispus*	
(Intercept)	-0.21 ± 0.19
Landscape type	-0.27 ± 0.32
Honeybee abundance	-0.00 ± 0.00
Landscape type x Honeybee abundance	0.00 ± 0.00



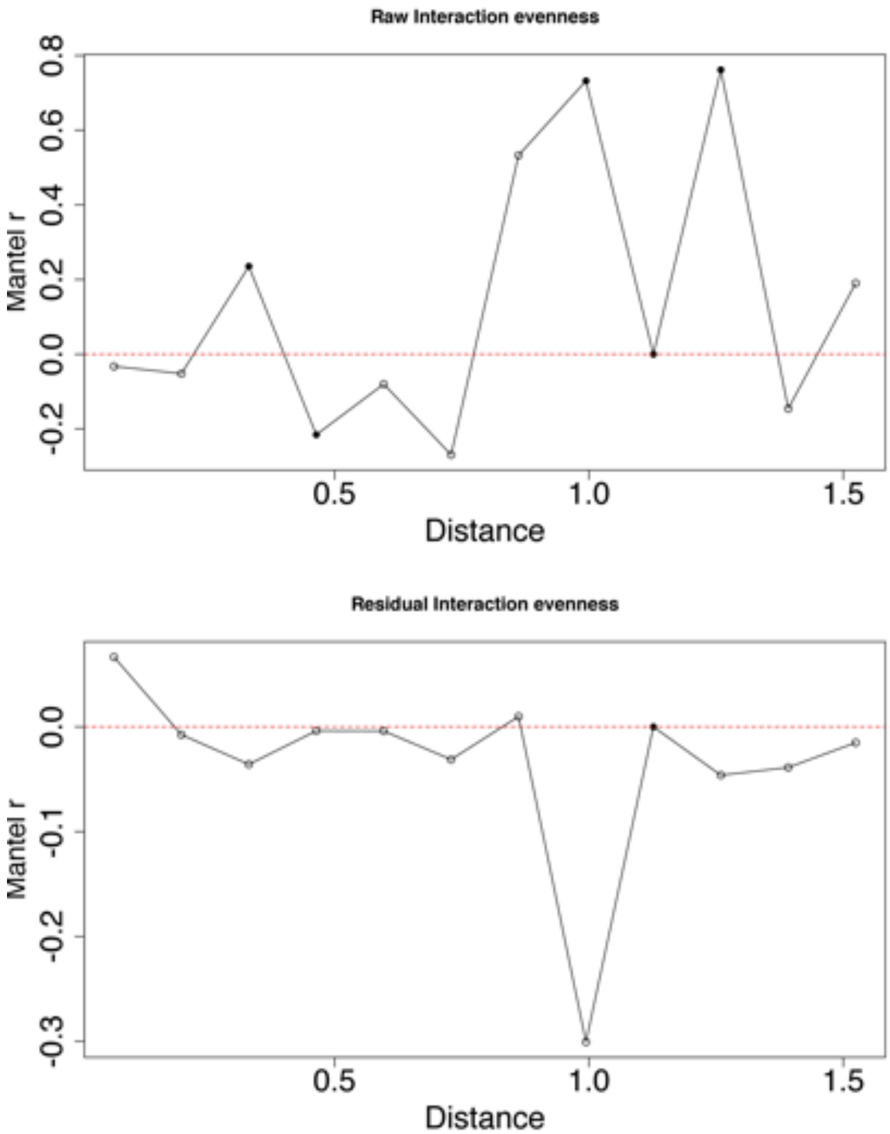
Supplementary Figure 1. Scatter-plots showing the effect of honeybee abundance (bees per 150 m^2) on three network metrics a) interaction evenness b) link density, c) link density for wild species only and d) complementary specialization for woodlands surrounded by high (orange) and low (green) orange grove cover.



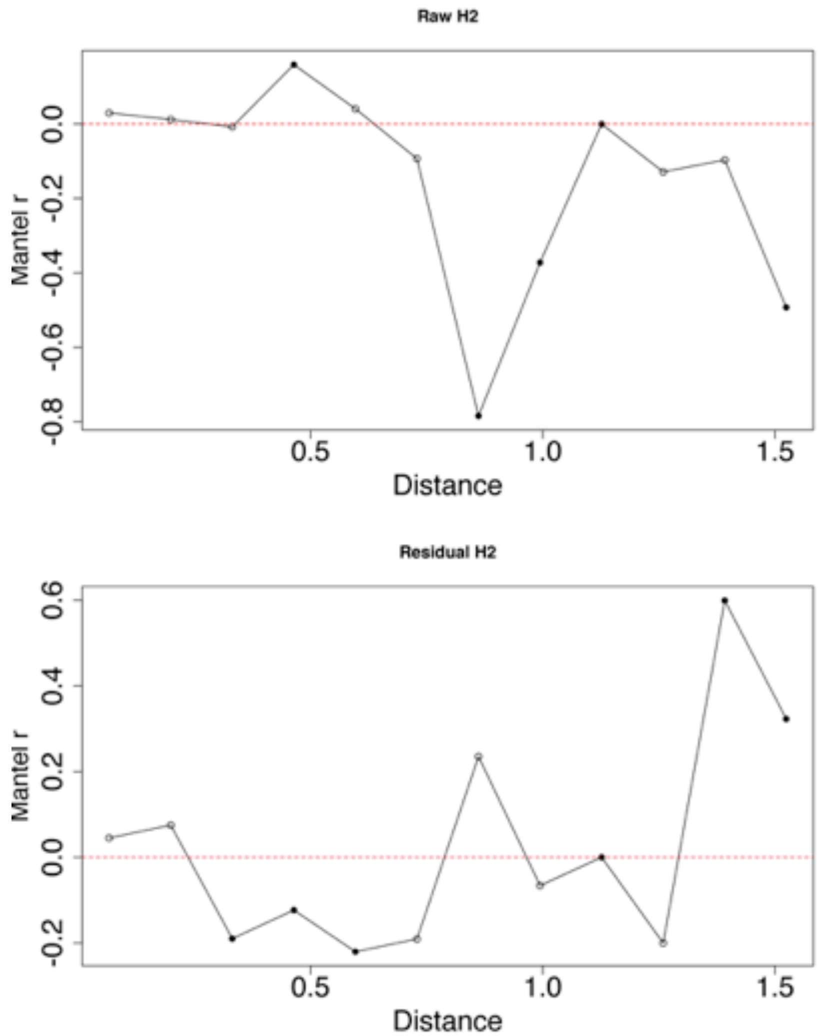
Supplementary Figure 2. Scatter-plot showing the effect of honeybee abundance (bees per 150 m^2) on functional complementarity in woodlands surrounded by high (orange) and low (green) orange grove cover at both time periods.



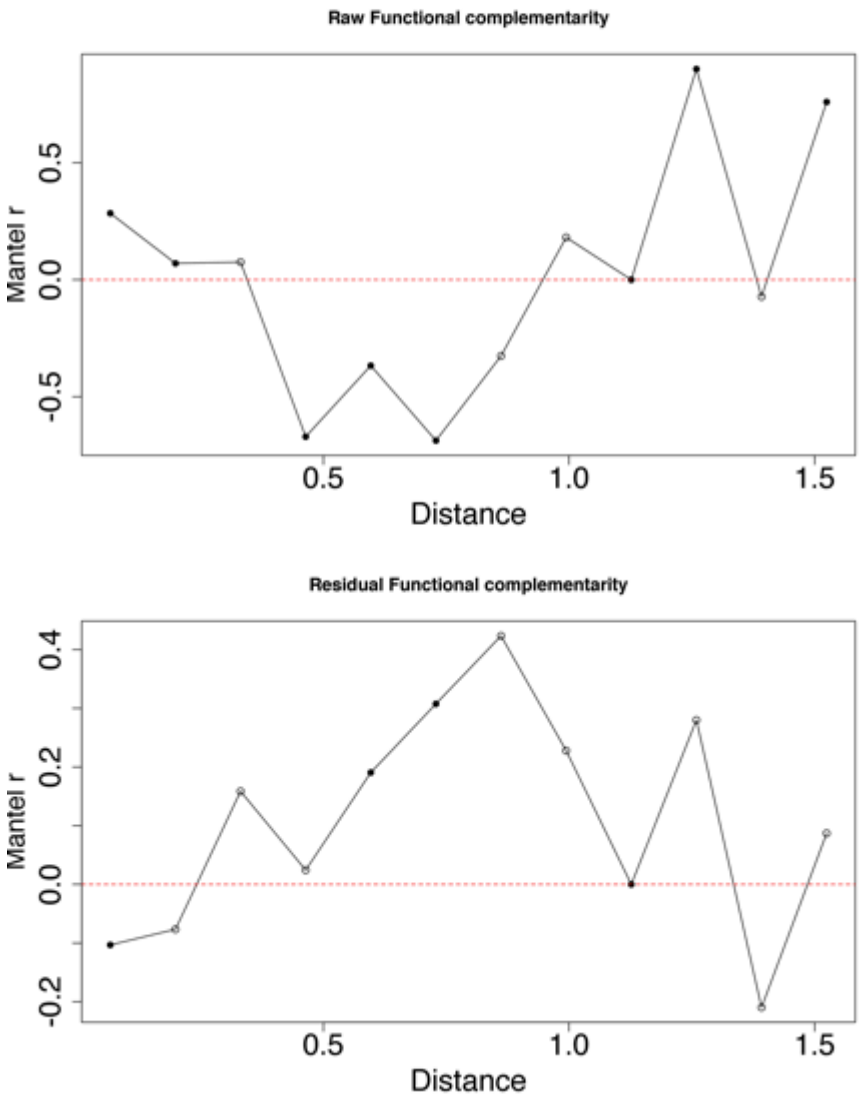
Supplementary Figure 3. Spatial autocorrelation between sites for raw and residual interaction turnover.



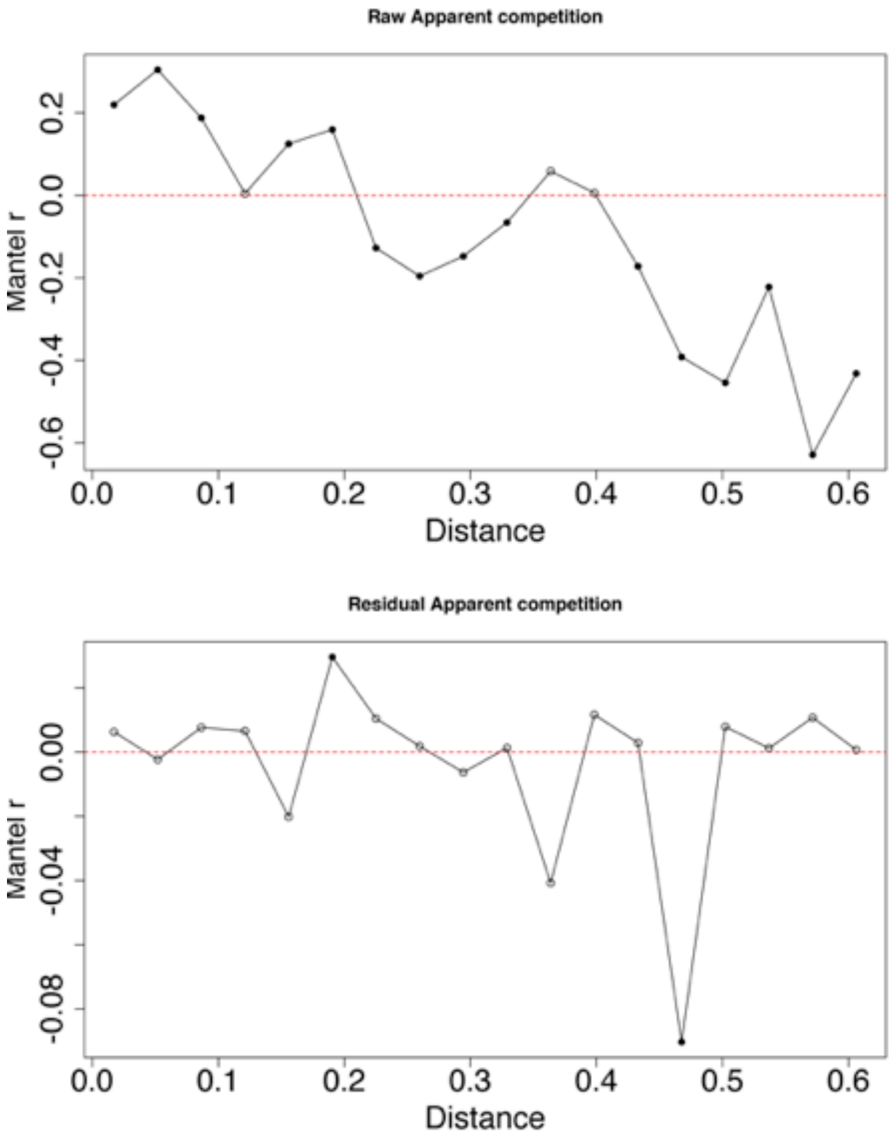
Supplementary Figure 4. Spatial autocorrelation between sites for raw and residual interaction evenness.



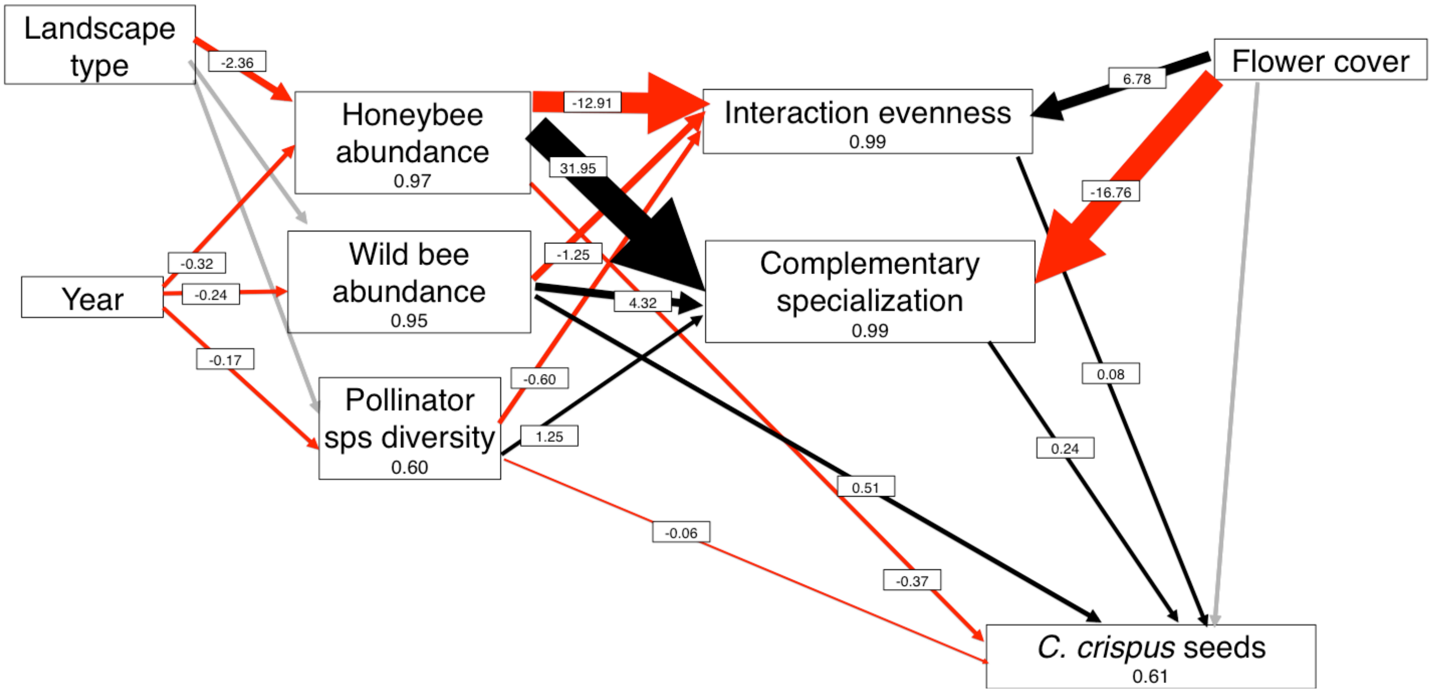
Supplementary Figure 5. Spatial autocorrelation between sites for raw and residual complementary specialization.



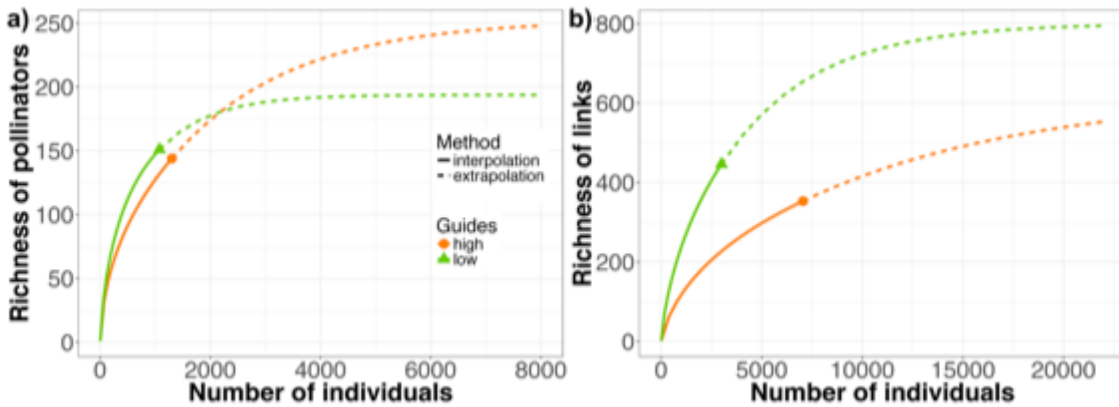
Supplementary Figure 6. Spatial autocorrelation between sites for raw and residual functional complementarity.



Supplementary Figure 7. Spatial autocorrelation between sites for raw and residual apparent competition.



Supplementary Figure 8. Structural equation model (SEM) exploring the effect of different landscape, network and pollinator guild variables on seed set for *Cistus crispus*. Each box represents the measured variables and arrows show relationships between variables. Black = positive relationships, red = negative relationships and grey = non-significant relationships (P> 0.05). Line width represents the magnitude of the regression coefficient for which all continuous variables have been standardized to allow for comparison. Conditional R^2 values are given within each response variable box. Analyses are done including random effect site in all cases as well as plant within site in the case of seeds. This analysis was a good fit for the data based on the comparison of Fisher's C statistic to a chi-square distribution (C = 7.54, P = 0.11).



Supplementary Figure 9. Accumulation curves of a) pollinator and b) plant-pollinator link richness with increasing sampling effort up to 100% sample coverage. Solid lines and points indicate observed richness while dashed lines show expected richness at increasing sample size, (i.e., extrapolated).