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Short communication

Simulated climate-warming increases Coleoptera activity-densities and reduces community diversity in a cereal crop

Sophie C.F. Berthe[a], Stéphane A.P. Derocles[a,*], David H. Lunt[a], Bruce A. Kimball[b], Darren M. Evans[a]

[a] School of Biological, Biomedical and Environmental Sciences, University of Hull, Hull HU6 7RX, UK
[b] U.S. Arid-Land Agricultural Research Center, USDA, Agricultural Research Service, 21881 North Cardon Lane, Maricopa, AZ 85138, USA

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ABSTRACT

Simulated climate-warming experiments have provided important insights into the response of terrestrial ecosystems, but few have examined the impacts on agricultural insects, particularly those associated with the ecosystem service of biological pest control. Within a spring-sown wheat crop, we artificially increased temperature by 2 °C and precipitation by 10% in a short-term (April to August 2013) replicated open-field experiment and examined the impacts on coleopteran (mainly Carabidae) diversity and 'activity-densities'. Diversity indices decreased as a result of warming but were not affected by extra precipitation. We found a significant increase in activity-densities of the four most trapped species due to warming, which was responsible for observed changes in diversity. However, Staphylinidae beetles were negatively affected by the warming treatments while other, less common species were not affected. We provide the first experimental evidence of climate-driven impacts on an important farmland insect community. We discuss the implications of our results in the context of biological control and top-down effects across trophic levels.

1. Introduction

In recent decades, changes in climate have caused significant impacts on ecosystems on all continents (IPCC, 2014). In northern Europe, climate models predict significant warming, an increase in both precipitation (mainly in winter) and the frequency of extreme weather events, which are likely to cause significant damage to agro-ecosystems (Olesen et al., 2011). With increasing evidence that present climate change is altering geographical ranges, population dynamics and phenologies of some insects (e.g. butterflies and moths, Altermatt, 2010), there is growing concern that global food security is threatened by the emergence and spread of crop pests and pathogens, some of which are moving polewards as a result of warming (Bebber et al., 2013). Insect pests and pathogens are currently responsible for the loss of up to 25–30% of crops in Europe and the United States of America, and this is predicted to rise as a result of global warming (Maxmen, 2013). Thus, modelling the impacts of climate change scenarios on agricultural insect pests, predators and their ecological interactions is a research priority (Luedeling et al., 2011; Ziter et al., 2012; Tylianakis et al., 2008; Schweiger et al., 2012). However, for future modelling projections to be accurate they need to be parameterised and validated by experimental evidence, which is mostly lacking. Furthermore, few studies have considered the response of insect predators to climate change, which are increasingly regarded as important for regulating future pest populations as some synthetic pesticides are phased out (e.g. EU Directive 2009/128/EC).

Experimental manipulations of temperature and precipitation have provided insights into the responses of terrestrial ecosystems, with warming generally stimulating total NPP, increasing ecosystem photosynthesis and respiration (Wu et al., 2011, for a review). To date, such studies have mostly focused on the responses of plants to simulated climate-warming but few have considered the response of animal communities, particularly in agro-ecosystems. Dong et al. (2013) were among the first to demonstrate that experimentally warming wheat fields can lead to an increase in pest aphid abundance. Buchholz et al. (2013) also showed increases in ground beetle, spider and grasshopper activity-densities under experimental grassland drought conditions, but generally lower diversity. However, to our knowledge, no study has examined the impacts of simulated climate change on insect

* Corresponding author.
E-mail addresses: berthe.sophie@gmail.com (S.C.F. Berthe), s.derocles@hull.ac.uk (S.A.P. Derocles), d.h.lunt@hull.ac.uk (D.H. Lunt), Bruce.Kimball@ARS.USDA.GOV (B.A. Kimball), d.evans@hull.ac.uk (D.M. Evans).

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predators within agro-ecosystems. For the first time, we assessed the effect of increased temperature and precipitation on an insect community of major economic importance: the Coleoptera consisting of ground beetles (Carabidae) and rove beetles (Staphylinidae). Coleoptera play a major role in ecosystem processes, provide natural pest control of a range of farmland insects and are an important food source for many farmland birds (Holland and Luff, 2000). As such, beetles are commonly used as a bioindicator because they are sensitive to environmental change (e.g. Buchholz et al., 2013; Rainio and Niemelä, 2003).

Our expectation is that as ectotherms, farmland beetle abundance would increase as a result of climate-warming rather than increased precipitation. Given that some beetle species react more readily to climate-warming than others (Buchholz et al., 2013), we predict that climate-warming will affect measures of beetle community diversity. We tested these hypotheses in a fully-replicated open-field experiment consisting of spring-sown wheat with a 2 °C temperature (corresponding to a best-case scenario by the 2080s in the UK; Murphy et al., 2009) and 10% precipitation increase, examining the impacts on beetle activity-densities (i.e. catch rate after controlling for temperature effects, Saska et al., 2013) and diversity.

2. Material and methods

2.1. Study site

The study was conducted in 2013 at Stockbridge Technology Centre (STC), North Yorkshire, UK (53°49′N–1°9′W), a conventional farm consisting of meadows and cereal crops used for field experiments (Appendix A in Supplementary material).

2.2. Experimental design and treatments

We established a replicated, randomized block open-field experiment (identical to that in Rollinson and Kaye, 2012) consisting of six replicates of four simulated climate-change treatments in a field of spring wheat (*Triticum aestivum* cultivar Tybalt). The four treatments consisted of: (W) 2 °C increase in temperature; (P) increase of precipitation by 10%; (WP) warming and precipitation treatments combined; and (C) control (ambient conditions) and were randomly allocated to each plot (Appendix A in Supplementary material). Experimental plots were 2 × 2 m and separated by 2 m of wheat to provide a buffer and allow the free movement of insects. The warming treatments (W and WP) involved suspending 165 cm × 15 cm MSR-2420 infrared heaters (Kalglo Electronics Inc., Bethlehem, PA, USA) 1.5 m above each plot, consistently heating during the day and at night (Kimball et al., 2012; Dong et al., 2013). A real-time proportional-integrative-derivative feedback system ensured constant temperature plot warming through infrared radiometer (IRR) monitoring of surface temperatures in warmed plots (Appendix A in Supplementary material). For the C and P plots, 'dummy' heaters of the same shape, size, and installation were used to mimic any potential shading effect of the warming equipment. Increased rainfall was simulated in the P and WP plots by adding 10% extra (based on STC mean monthly rainfall data collected between 2002 and 2012) collected rainwater to the plots with a watering can. We added the following water each week: 13 l in April; 19 l in May; 24 l in June; 26 l in July and 30 l in August, amounting to 407 l in total for each plot. All treatments commenced with the sowing of spring wheat on 13th April 2013. Herbicide treatments were applied to the experimental field on 2nd April 2013 and on 13th May 2013—our aim was to allow some weed growth without out-competing the wheat.

2.3. Insect collection

A pitfall trap (diameter = 5 cm; height = 7 cm, Lövei and Sunderland, 1996) was placed in the centre of each plot. Sampling was undertaken weekly from 6th June to 14th August 2013. No preservative liquid (as suggested by Lövei and Sunderland, 1996) was added to the traps: our aim was to capture living individuals to preserve the quality of the DNA for subsequent analysis. Although predation between Coleoptera could be a problem, we found very few insect remains in the traps suggesting that this was not the case. Specimens were collected within 24 h and frozen at −20 °C. Carabidae species were identified to the species-level according to Luff (2007) except for the genus *Amara* and the Staphylinidae.

2.4. Statistical analysis

Pitfall trapping is widely used for sampling carabid populations, but according to Saska et al. (2013) this technique yields biased estimates of abundance ('activity-density') because individual activity – which is affected by temperature (in their study between 4.97 and 8.63% increase in catch size per 1 °C increase in temperature) – affects the rate of catch. We mathematically corrected the number of individuals trapped in the warmed plots by 8.63% per 1 °C increase in temperature (Appendix A3 in Supplementary material). Climate-change may affect the activity-density of a limited number of species. To examine the differing effects of climate change on beetle species, diversity indices (Shannon index, Simpson index and Evenness) for each plot were then calculated using package 'vegan' (Oksanen et al., 2013) in R 3.0 (R Development Core Team, 2013). As some plot-level species accumulation curves did not reach an asymptote (Appendix B in Supplementary material), we estimated species richness using functional extrapolation in EstimateS 9.1.0 (100 randomizations; Chao2 estimator; Colwell et al., 2012). We examined the effects of experimental treatment on the corrected number of Coleoptera trapped, species richness, evenness, Simpson and Shannon indices using generalized linear models (GLM, family Gaussian, Appendix A3 in Supplementary material). For comparison, we conducted an additional analysis based on rarefied data

Table 1
Beetle species richness, number of individuals trapped and diversity per plot. S.E.: Standard error. Statistically significant effects of treatment are highlighted in bold.

	Total species richness		Species richness estimated		Raw capture		Corrected capture		Simpson index		Shannon index		Evenness	
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Control	10.83	0.75	15.43	2.51	63	4.31	63	4.31	0.79	0.02	1.88	0.1	0.79	0.03
Precipitation	9.83	0.31	15.15	2.46	69	7.21	68.83	7.27	0.77	0.03	1.75	0.09	0.77	0.04
Warming	11.33	0.56	16.38	0.88	122.83	11.6	108.17	11.97	0.7	0.02	1.58	0.07	0.65	0.03
W + P	10.83	0.6	13.69	1.78	132.83	15.71	115.7	15.15	0.74	0.01	1.67	0.06	0.7	0.02
GLM	*F*-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value
↑ Precipitation	1.763	0.199	0.558	0.464	0.594	0.45	0.559	0.464	0.159	0.695	0.028	0.87	0.242	0.628
↑ T°C	1.763	0.199	0.017	0.898	35.475	$<$ **0.001**	6.294	**0.004**	6.066	**0.023**	5.104	**0.035**	12.47	**0.002**

(Appendix B in Supplementary material). The effect of experimental treatments on the number of individuals trapped for each species per plot was assessed with the contrasts method using the Esticon function in the R package 'DoBy' (Hojsgaard, 2004). For comparison, we performed the same statistical analysis based on the raw, uncorrected data (Appendix C in Supplementary material).

3. Results

A total of 2320 Coleoptera were caught, representing 2206 carabid beetles (belonging to 23 species and to the genus *Amara*), and 114 Staphylinidae.

Experimental warming had a statistically significant positive effect on total number of beetles trapped after correction (GLM, df = 1; F = 6.294; p = 0.004), and a negative effect on diversity ($p < 0.05$ for all three indices, Table 1), but not on species richness (although this was marginally significant using rarefied data; Appendix B in Supplementary material). We found no effect of sampling period and plot (Appendix D in Supplementary material). Increased precipitation had no effect on any of our response variables. Warming significantly increased the number of individuals trapped for most coleopteran species after correction; Staphylinidae showed however a significant decrease in their capture in warmed plots (Fig. 1). The corrected number of individuals trapped showed the same patterns as the raw data (Appendix C in Supplementary material).

4. Discussion

For the first time, we provide experimental evidence that simulated climate-warming increases the activity-densities but reduces the diversity of an important group of farmland insect predators. After controlling for the likely effect of temperature on Coleoptera activity and subsequent catch rate (Saska et al., 2013), significantly more Coleoptera were trapped in the experimentally warmed plots. The observed increases in capture were mainly driven by the four most common species *Pseudoophonus rufipes, Pterostychus melanarius, Calathus fuscipes* and *Harpalus affinis*, significantly affecting community diversity and evenness. In contrast, climate-warming significantly decreased the capture of Staphylinidae. We found no specific trait shared exclusively by the four common species that could explain their particular sensitivity to climate-change. *P. rufipes, P. melanarius* and *H. affinis* are nevertheless considered as eurytopic and can dominate agro-ecosystems because they are highly tolerant to habitat disturbance and modification (Luff, 2002). A similar result was found recently by Buchholz et al. (2013) where a simulated drought experiment (i.e. warming a grassland community of arthropods) disproportionately increased the abundance of *P. rufipes* (referred to in that study by its synonymous name *Harpalus rufipes*), but overall reduced beetle diversity. Together, our results suggest that climate-warming may promote common and highly adaptable beetle species at the cost of others (such as the Staphylinidae). However, more research is necessary, especially to account for inter-annual spatial variation, and different habitat types (e.g. crop and non-crop). As stated by Buchholz et al. (2013), wider spatial and temporal scales could potentially influence findings such as ours.

Although the impacts of simulated climate-change have been demonstrated for a small but growing number of arthropod groups (e.g. Dong et al., 2013; Buchholz et al., 2013), its influence on trophic interactions is still unclear. *P. rufipes, C. fuscipes* and *H. affinis* are known to consume plants and other arthropods, and an increase in the activity-densities of ground beetles could have top-down effects on the entire agro-ecosystem. In terms of positive benefits to farmers, climate-driven increases in the activity-densities of beetle species might enhance the biological control of major agricultural pests (Holland and Luff, 2000) and may enhance weed regulation (e.g. weed seed consumption by *P. rufipes* and *H. affinis* increases at higher temperatures, Saska et al., 2010). However, an increase in beetle activity-densities might also lead to higher intraguild predation (Raso et al., 2014) and thus a loss of other species providing biological control. Future studies should examine the response of species interactions within and across trophic levels to better understand the impacts of climate change on farmland networks (Bohan et al., 2013).

Our results show that important pest-controlling insects within agro-ecosystems respond rapidly to simulated climate-warming, with potentially positive impacts for cereal growers. However, determining the functional response of agro-ecosystems to

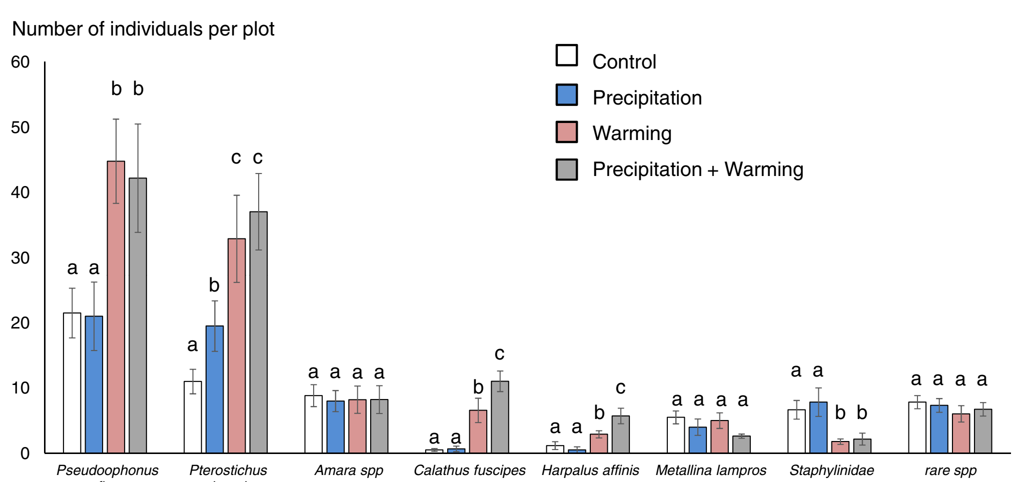

Fig. 1. Impact of the experimental treatments on the number of individuals trapped after correction. Error bars indicate the standard error. Treatments were compared two by two for each species. Letters indicate a significant difference ($p < 0.05$; GLM, contrasts method).

climate-warming requires an understanding of the complex ways in which multiple species interact at the farm-scale (Bohan et al., 2013). For Coleoptera, this will involve a better understanding of plant–prey–predator interactions under a range of environmental scenarios and spatial scales. Molecular approaches that analyse gut contents are a promising way of elucidating such complex interactions (e.g. Raso et al., 2014), enabling them to be linked into wider ecological networks for novel analysis (Pocock et al., 2012).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2015.05.001.

References

Altermatt, F., 2010. Climatic warming increases voltinism in European butterflies and moths. Proc. R. Soc. B 277, 1281–1287. doi:http://dx.doi.org/10.1098/rspb.2009.1910.

Bebber, D.P., Ramotowski, M.A.T., Gurr, S.J., 2013. Crop pests and pathogens move polewards in a warming world. Nat. Clim. Change 3, 985–988. doi:http://dx.doi.org/10.1038/nclimate1990.

Bohan, D.A., Raybould, A., Mulder, C., Woodward, G., Tamaddoni-Nezhad, A., Bluthgen, N., Pocock, M.J.O., Muggleton, S., Evans, D.M., Astegiano, J., et al., 2013. Networking agroecology: integrating the diversity of agroecosystem interactions. In: Woodward, G., Bohan, D.A. (Eds.), Advances in Ecological Research. Academic Press, Amsterdam, The Netherlands, pp. 1–67. doi:http://dx.doi.org/10.1016/B978-0-12-420002-9.00001-9.

Buchholz, S., Rolfsmeyer, D., Schirmel, J., 2013. Simulating small-scale climate change effects–lessons from a short-term field manipulation experiment on grassland arthropods. Insect Sci. 20, 662–670. doi:http://dx.doi.org/10.1111/j.1744-7917.2012.01556.x.

Colwell, R.K., Chao, A., Gotelli, N.J., Lin, S.-Y., Mao, C.X., Chazdon, R.L., Longino, J.T., 2012. Models and estimators linking individual-based and sample-based rarefaction, extrapolation, and comparison of assemblages. J. Plant Ecol. 5, 3–21. doi:http://dx.doi.org/10.1093/jpe/rtr044.

Dong, Z., Hou, R., Ouyang, Z., Zhang, R., 2013. Tritrophic interaction influenced by warming and tillage: a field study on winter wheat, aphids and parasitoids. Agric. Ecosyst. Environ. 181, 144–148. doi:http://dx.doi.org/10.1016/j.agee.2013.09.009.

Hojsgaard, S., 2004. Statistical inference in context specific interaction models for contingency tables. Scand. J. Stat. 31, 143–158. doi:http://dx.doi.org/10.1111/j.1467-9469.2004.00378.x.

Holland, J.M., Luff, M.L., 2000. The effects of agricultural practices on carabidae in temperate agroecosystems. Integrated Pest Manage. Rev. 5, 109–129. doi:http://dx.doi.org/10.1023/A:1009619309424.

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, NY, USACambridge University Press.

Kimball, B.A., White, J.W., Wall, G.W., Ottman, M.J., 2012. Infrared-warmed and un-warmed wheat vegetation indices coalesce using canopy-temperature-based growing degree days. Agron. J. 104, 114–118. doi:http://dx.doi.org/10.2134/agronj2011.0144.

Lövei, G.L., Sunderland, K.D., 1996. Ecology and behavior of ground beetles (Coleoptera: Carabidae). Annu. Rev. Entomol. 41, 231–256. doi:http://dx.doi.org/10.1146/annurev.en.41.010196.001311.

Luedeling, E., Steinmann, K.P., Zhang, M., Brown, P.H., Grant, J., Girvetz, E.H., 2011. Climate change effects on walnut pests in California. Global Change Biol. 17, 228–238. doi:http://dx.doi.org/10.1111/j.1365-2486.2010.02227.x.

Luff, M.L., 2002. Carabid assemblage organization and species composition. In: Holland, J.M. (Ed.), The Agroecology of Carabid Beetles. Intercept Limited, Hampshire, UK, pp. 41–79.

Luff, M.L., 2007. The Carabidae (ground beetles) of Britain and Ireland. Royal Entomological Society, St. Albans, UK.

Maxmen, A., 2013. Crop pests: under attack. Nature 501, 15–17. doi:http://dx.doi.org/10.1038/501S15a.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T. P., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R.A., 2009. UK Climate Projections Science Report: Climate Change Projections. Met Office Hadley Centre, Exeter, UK.

Oksanen, J., Blanchet, G.F., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Wagner, H., 2013. Vegan: Community Ecology Package. R package version 2. 0-10. http://CRAN.R-project.org/package=vegan

Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34 (2), 96–112. doi:http://dx.doi.org/10.1016/j.eja.2010.11.003.

Pocock, M.J.O., Evans, D.M., Memmott, J., 2012. The robustness and restoration of a network of ecological networks. Science 335, 973–977. doi:http://dx.doi.org/10.1126/science.1214915.

R Development Core Team, 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rainio, J., Niemelä, J., 2003. Ground beetles (Coleoptera: Carabidae) as bioindicators. Biodivers. Conserv. 12, 487–506. doi:http://dx.doi.org/10.1023/A:1022412617568.

Raso, L., Sint, D., Mayer, R., Plangg, S., Recheis, T., Brunner, S., Kaufmann, R., Traugott, M., 2014. Intraguild predation in pioneer predator communities of alpine glacier forelands. Mol. Ecol. 23, 3744–3754. doi:http://dx.doi.org/10.1111/mec.12649.

Rollinson, C.R., Kaye, M.W., 2012. Experimental warming alters spring phenology of certain plant functional groups in an early successional forest community. Global Change Biol. 18, 1108–1116. doi:http://dx.doi.org/10.1111/j.1365-2486.2011.02612.x.

Saska, P., Martinkova, Z., Honek, A., 2010. Temperature and rate of seed consumption by ground beetles (Carabidae). Biol. Control 52, 91–95. doi:http://dx.doi.org/10.1016/j.biocontrol.2009.07.016.

Saska, P., van der Werf, W., Hemerik, L., Luff, M.L., Hatten, T.D., Honek, A., 2013. Temperature effects on pitfall catches of epigeal arthropods: a model and method for bias correction. J. Appl. Ecol. 50, 181–189. doi:http://dx.doi.org/10.1111/1365-2664.12023.

Schweiger, O., Heikkinen, R.K., Harpke, A., Hickler, T., Klotz, S., Kudrna, O., Kuhn, I., Poyry, J., Settele, J., 2012. Increasing range mismatching of interacting species under global change is related to their ecological characteristics. Global Ecol. Biogeogr. 21, 88–99. doi:http://dx.doi.org/10.1111/j.1466-8238.2010.00607.x.

Tylianakis, J.M., Didham, R.K., Bascompte, J., Wardle, D.A., 2008. Global change and species interactions in terrestrial ecosystems. Ecol. Lett. 11, 1351–1363. doi:http://dx.doi.org/10.1111/j.1461-0248.2008.01250.x.

Wu, Z., Dijkstra, P., Koch, G.W., Peñuselas, J., Hungate, B.H., 2011. Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation. Global Change Biol. 17, 927–942. doi:http://dx.doi.org/10.1111/j.1365-2486.2010.02302.x.

Ziter, C., Robinson, E.A., Newman, J.A., 2012. Climate change and voltinism in Californian insect pest species: sensitivity to location, scenario and climate model choice. Global Change Biol. 18, 2771–2780. doi:http://dx.doi.org/10.1111/j.1365-2486.2012.02748.x.