

***Supporting Online Material for***

**Long-range seasonal migration in insects: mechanisms, evolutionary drivers and ecological consequences**

Jason W. Chapman\*, Don R. Reynolds and Kenneth Wilson

\* To whom correspondence should be addressed: E-mail: [\*jason.chapman@rothamsted.ac.uk\*](mailto:jason.chapman@rothamsted.ac.uk)

**Table S1. Technological developments that have been utilised in recent studies of long-range migration in large insects.**

Techniques		Examples of species studied	References
<b>Remote sensing and radio technologies*</b>			
Radar	Vertical-looking entomological radar (VLR) with ZLC configuration (zenith-pointing linear-polarized conical scan)	<i>Autographa gamma</i> (silver-Y moth) <i>Helicoverpa armigera</i> (cotton bollworm) <i>Mythimna separata</i> (oriental armyworm moth) <i>Loxostege sticticalis</i> (beet webworm moth) <i>Chortoicetes terminifera</i>	Many studies – see references in Chapman et al. 2011; Drake & Reynolds 2012
	Meteorological research or Doppler weather radars	<i>C. terminifera</i> (Australian plague locust) <i>Helicoverpa zea</i> (corn earworm)	Rennie et al. 2012; Westbrook et al. 2013
Radio-tracking	-----	<i>Anax junius</i> (common green darner dragonfly)	Wikelski et al. 2006 See Kissling et al. 2013 for a review of radio-tracking of insect <i>movement</i> in general.
Satellite remote sensing	Indices such as NDVI (normalized difference vegetation index) and satellite-derived rainfall estimation products used to monitor habitat condition	<i>Schistocerca gregaria</i> (desert locust) <i>C. terminifera</i>	Cressman 2013 Deveson 2013
<b>Vertical-pointing searchlight trap</b>	Attracts and captures high-altitude migrants	<i>Spodoptera exigua</i> (beet armyworm) <i>H. armigera</i> , and other moths <i>Pantala flavescens</i> (wandering glider dragonfly)	e.g. Feng et al. 2003, 2009 Feng et al. 2006

<b>Atmospheric trajectory modelling</b> (in combination with trapping data)	Numerical weather forecasting and particle dispersion models (e.g. UK Met Office's NAME, ARL/NOAA's HYSPLIT, Penn State University/NCAR's MM5 and NCAR's WRF), sometimes incorporating additional modelling to capture features of insect migration	Several species from the Sphingidae ( <i>Macroglossum pyrrhosticta</i> ), Crambidae (e.g. <i>Spoladea recurvalis</i> , <i>Cnaphalocrocis medinalis</i> , <i>Maruca vitrata</i> ) and Noctuidae (e.g. <i>H. armigera</i> , <i>Mythimna separata</i> , <i>Spodoptera litura</i> , <i>Spodoptera exempta</i> ) <i>H. zea</i> <i>A. gamma</i> <i>S. litura</i> <i>Choristoneura fumiferana</i> (spruce budworm moth)	Kawazu, et al. 2008  Westbrook 2008 Chapman et al. 2010, 2012 Tojo et al. 2013 Sturtevant et al. 2013
<b>Computerised Flight-mills</b>	Laboratory assessments of flight potential	<i>H. zea</i> <i>H. armigera</i> <i>Agrilus planipennis</i> (emerald ash borer beetle)	Beerwinkle et al. 1995 See Fig. 4 in main text Taylor et al. 2010
<b>Stable isotope analyses</b>	Stable hydrogen isotope ( $\delta D$ )	<i>Danaus plexippus</i> (Monarch butterfly)  <i>Vanessa atalanta</i> (red admiral)	Dockx et al. 2004; Miller et al. 2012; Flockhart et al. 2013  Brattström et al. 2010
	Stable carbon ( $\delta^{13}C$ )	<i>Pantala flavescens</i> (wandering glider dragonfly) <i>A. junius</i> <i>H. zea</i> <i>D. plexippus</i>	Hobson et al. 2012a Hobson et al. 2012b  Gould et al. 2002 Dockx et al. 2004; Flockhart et al. 2013
	Strontium isotope ratio ( $^{87}Sr / ^{86}Sr$ ) and others (feasibility study)	<i>H. armigera</i>	Holder et al. 2014
<b>Chemical tracers</b>	Cardenolide fingerprinting by thin-layer chromatography	<i>D. plexippus</i>	Dockx et al. 2004

<b>Genetic markers</b>	Mitochondrial haplotypes	<i>Trichoplusia ni</i> (cabbage looper moth) <i>S. frugiperda</i> <i>Plutella xylostella</i> (diamondback moth) <i>S. exempta</i> (African armyworm moth)	Franklin et al. 2011 Nagoshi et al. 2012 Wei et al. 2013 Graham & Wilson 2012
	Microsatellite markers	<i>H. armigera</i> <i>D. plexippus</i> <i>P. xylostella</i> <i>S. exempta</i>	Scott et al. 2005 Lyons et al. 2012 Wei et al. 2013 Ibrahim et al. 2004
	Amplified fragment length polymorphism (AFLP)	<i>L. sticticalis</i> <i>T. ni</i>	Jiang et al. 2010 Franklin et al. 2011
	Random amplified polymorphic DNA polymerase chain reaction (RAPD-PCR)	<i>H. armigera</i>	Zhou et al. 2000
	Expressed sequence tags (EST)	<i>D. plexippus</i>	Zhu et al. 2009

\* Note that many of the available telemetric techniques for studies of animal migration and movement are not suitable for studies of insect migratory flight – in many cases the tracking devices e.g. radio-telemetry transmitters, GPS-based devices or light-level geolocation loggers are too heavy for the vast majority of insects, or they function only over short ranges e.g. RFID (Radio Frequency Identification) tags.

## REFERENCES (for Table S1)

- Beerwinkle, K.R., Lopez, J.D. Jr, Cheng, D., Lingren, P.D. & Meola, R.W. (1995). Flight potential of feral *Helicoverpa zea* (Lepidoptera: Noctuidae) males measured with a 32-channel, computer-monitored flight mill system. *Environ.Entomol.*, 24, 1122–1130.
- Brattström, O., Bensch, S., Wassenaar, L.I., Hobson, K.A. & Åkesson, S. (2010). Understanding the migration ecology of European red admirals *Vanessa atalanta* using stable hydrogen isotopes. *Ecography*, 33, 720–729.
- Chapman, J.W., Nesbit, R.L., Burgin, L.E., Reynolds, D.R., Smith, A.D., Middleton, D.R. et al. (2010). Flight orientation behaviors promote optimal migration trajectories in high-flying insects. *Science*, 327, 682-685.
- Chapman, J.W., Drake, V.A. & Reynolds, D.R. (2011). Recent insights from radar studies of insect flight. *Annu. Rev. Entomol.*, 56, 337-356.

- Chapman, J.W., Bell, J.R., Burgin, L.E., Reynolds, D.R., Pettersson, L.B., Hill, J.K. et al. (2012). Seasonal migration to high latitudes results in major reproductive benefits in an insect. *Proc. Natl. Acad. Sci. USA*, 109 (37), 14924-14929.
- Cressman, K. (2013). Role of remote sensing in desert locust early warning. *J. Appl. Remote Sens.*, 7, 075098.
- Deveson, E.D. (2013). Satellite normalized difference vegetation index data used in managing Australian plague locusts. *J. Appl. Remote Sens.*, 7, 075096.
- Dockx, C., Brower, L.P., Wassenaar, L.I. & Hobson, K.A. (2004). Do North American monarch butterflies travel to Cuba? Stable isotope and chemical tracer techniques. *Ecol. Appl.*, 14, 1106–1114.
- Drake, V.A. & Reynolds, D.R. (2012). *Radar Entomology: Observing Insect Flight and Migration*. CABI, Wallingford, UK.
- Feng, H.-Q., Wu, K.-M., Cheng, D.-F. & Guo, Y.-Y. (2003). Radar observations of the autumn migration of the beet armyworm *Spodoptera exigua* (Lepidoptera: Noctuidae) and other moths in northern China. *Bull. Entomol. Res.*, 93, 115–124.
- Feng, H.-Q., Wu, K.-M., Ni, Y.-X., Cheng, D.-F. & Guo, Y.Y. (2006). Nocturnal migration of dragonflies over the Bohai Sea in northern China. *Ecol. Entomol.*, 31, 511–520.
- Feng, H.-Q., Wu, X.-F., Wu, B. & Wu, K.-M. (2009). Seasonal migration of *Helicoverpa armigera* (Lepidoptera: Noctuidae) over the Bohai Sea. *J. Econ. Entomol.*, 102, 95–104.
- Flockhart, D.T.T., Wassenaar, L.I., Martin, T.G., Hobson, K.A., Wunder, M.B. & Norris, D.R. (2013). Tracking multi-generational colonization of the breeding grounds by monarch butterflies in eastern North America. *Proc. Roy. Soc. B.*, 280, doi: 10.1098/rspb.2013.1087.
- Franklin, M.T., Ritland, C.E. & Myers, J.H. (2011). Genetic analysis of cabbage loopers, *Trichoplusia ni* (Lepidoptera: Noctuidae), a seasonal migrant in western North America. *Evol. Appl.*, 4, 89–99.
- Gould, F., Blair, N., Reid, M., Rennie, T.L., Lopez, J. & Micinski, S. (2002). *Bacillus thuringiensis*-toxin resistance management: stable isotope assessment of alternate host use by *Helicoverpa zea*. *Proc. Natl. Acad. Sci. USA*, 99, 16581–16586.
- Graham, R.I. & Wilson K (2012). Male-killing *Wolbachia* and mitochondrial selective sweep in a migratory African insect. *BMC Evolutionary Biology*, 12, 204, doi:10.1186/1471-2148-12-204.
- Hobson, K.A., Anderson, R.C., Soto, D.X. & Wassenaar, L.I. (2012a). Isotopic evidence that dragonflies (*Pantala flavescens*) migrating through the Maldives come from the northern Indian subcontinent. *PLoS ONE*, 7 (12), e52594.
- Hobson, K.A., Soto, D.X., Paulson, D.R., Wassenaar, L.I. & Matthews, J.H. (2012b). A dragonfly ( $\delta^2\text{H}$ ) isoscape for North America: a new tool for determining natal origins of migratory aquatic emergent insects. *Methods Ecol. Evol.* 3, 766–772.

- Holder, P.W., Armstrong, K., Van Hale, R., Millet, M.-A., Frew, R. et al. (2014). Isotopes and trace elements as natal origin markers of *Helicoverpa armigera* – an experimental model for biosecurity pests. *PLoS ONE*, 9 (3), e92384.
- Ibrahim, K.M., Yassin, Y. & Elguzouli, A. (2004). Polymerase chain reaction primers for polymorphic microsatellite loci in the African armyworm, *Spodoptera exempta* (Lepidoptera : Noctuidae). *Mol. Ecol. Notes*, 4, 653-655.
- Jiang, X.F., Cao, W.J., Zhang, L. & Luo, L.Z. (2010). Beet webworm (Lepidoptera: Pyralidae) migration in China: evidence from genetic markers. *Environ. Entomol.*, 39, 232–42.
- Kawazu, K., Otuka, A., Adati, T., Tonogouchi, H. & Yase, J. (2008). Lepidoptera captured on the East China Sea in 2005 and predicted migration sources. *Entomol. Sci.*, 11, 315–322.
- Kissling, W.D., Pattemore, D.E. & Hagen, M. (2014). Challenges and prospects in the telemetry of insects. *Biol. Rev. (Cambridge)*, doi: 10.1111/brv.12065.
- Lyons, J.I., Pierce, A.A., Barribeau, S.M., Sternberg, E.D., Mongue, A.J. & De Roode, J.C. (2012). Lack of genetic differentiation between monarch butterflies with divergent migration destinations. *Mol. Ecol.*, 21, 3433–44.
- Miller, N.G., Wassenaar, L.I., Hobson, K.A. & Norris D.R. (2012). Migratory connectivity of the Monarch butterfly (*Danaus plexippus*): Patterns of spring re-colonization in eastern North America. *PLoS ONE*, 7 (3), e31891.
- Nagoshi R.N., Adamczyk, J.J. Jr, Meagher, R.L., Gore J. & Jackson, R. (2007). Using stable isotope analysis to examine fall armyworm (Lepidoptera: Noctuidae) host strains in a cotton habitat. *J. Econ. Entomol.*, 100, 1569–1576.
- Nagoshi, R.N., Meagher, R.L. & Hay-Roe, M. (2012). Inferring the annual migration patterns of fall armyworm (Lepidoptera: Noctuidae) in the United States from mitochondrial haplotypes. *Ecol. & Evol.*, 2, 1458–1467.
- Rennie, S.J. (2013). Common orientation and layering of migrating insects in southeastern Australia observed with a Doppler weather radar. *Meteorol. Appl.*, DOI: 10.1002/met.1378.
- Scott, K.D., Lawrence, N., Lange, C.L., Scott, L.J., Wilkinson, K.S., Merritt, M.A. et al (2005). Assessing moth migration and population structuring in *Helicoverpa armigera* (Lepidoptera: Noctuidae) at the regional scale: example from the Darling Downs, Australia. *J. Econ. Entomol.*, 98, 2210–2219.
- Sturtevant, B.R., Achtemeier, G.L., Charney, J.J., Anderson, D.P., Cooke, B.J. & Townsend, P.A. (2013). Long-distance dispersal of spruce budworm (*Choristoneura fumiferana* Clemens) in Minnesota (USA) and Ontario (Canada) via the atmospheric pathway. 2013. *Agric. Forest Meteorol.*, 168, 186–200.

- Taylor, R.A.J., Bauer, L.S., Poland, T.M. & Windell, K.N. (2010). Flight performance of *Agrilus planipennis* (Coleoptera: Buprestidae) on a flight mill and in free flight. *J. Insect Behav.*, 23, 128–148.
- Théry, M. and GomezTojo, S., Ryuda, M., Fukuda, T., Matsunaga, T., Choi, D. & Otuka, A. (2013). Overseas migration of the common cutworm, *Spodoptera litura* (Lepidoptera: Noctuidae), from May to mid-July in East Asia. *Appl. Entomol. Zool.*, 48, 131–140.
- Wei, S.-J., Shi, B.-C., Gong, Y.-J., Jin, G.-H., Chen, X.-X. & Meng, X.-F. (2013). Genetic structure and demographic history reveal migration of the diamondback moth *Plutella xylostella* (Lepidoptera: Plutellidae) from the southern to northern regions of China. *PLoS ONE* 8 (4), e59654.
- Westbrook, J.K. (2008). Noctuid migration in Texas within the nocturnal aeroecological boundary layer. *Integr. Comp. Biol.*, 48, 99–106.
- Westbrook, J.K., Eyster, R.S. & Wolf, W.W. (2013). WSR-88D doppler radar detection of corn earworm moth migration. *Int. J. Biometeorol.*, DOI 10.1007/s00484-013-0676-5.
- Wikelski, M., Moskowicz, D., Adelman, J.S., Cochran, J., Wilcove, D.S. & May, M.L. (2006). Simple rules guide dragonfly migration. *Biol. Lett.*, 2, 325–329.
- Zhou, X., Faktor, O., Applebaum, S.W. & Coll, M. (2000). Population structure of the pestiferous moth *Helicoverpa armigera* in the Eastern Mediterranean using RAPD analysis. *Heredity* 85, 251–256.
- Zhu, H., Gegear, R.J., Casselman, A., Kanginakudru, S. & Reppert S.M. (2009). Defining behavioral and molecular differences between summer and migratory monarch butterflies. *BMC Biology*, 7, 14.