Insect population trends: why should we care, what do we know, and where do we go next?

With regard to number of species, insects are the most successful group on the planet (Homburg *et al*., 2019) and represent extensive unique and overlapping functions. Pollination by Lepidoptera, Hymenoptera, and Diptera strongly influences crop yields and profits (Habel *et al*., 2019), while biological pest control is a highly valued service provided by Lepidoptera, Diptera, Coleoptera, and Odonata. Insects recycle organic matter, and are a major link in the food web between primary producers and consumers (Sánchez-Bayo & Wyckhuys, 2019; Wagner *et al*., 2021b). Without these services, we threaten global ecosystem health and food security (Powney *et al*., 2019), which is particularly apparent in the global south where reliance on insect pollinated crops is high (Dicks *et al*., 2021). Despite considerable variation in methodology and conclusions of studies on population trends, we have enough evidence to warrant immediate further study and action (Montgomery *et al*., 2020).

Insects face a multitude of threats, with habitat and climate change most widely discussed (Outhwaite *et al*., 2022). Habitat change encompasses land-use change, pollution, and invasive species (Habel *et al*., 2019; Powney *et al*., 2019; Sánchez-Bayo & Wyckhuys, 2019). Of these, land-use change (including agricultural intensification, urbanisation, and industrialisation) has been identified as a predictor of species occurrence by several studies (Newbold *et al*., 2014; Gray *et al*., 2016; Newbold *et al*., 2016) though there are substantial differences in effect between tropical and non-tropical habitats (Millard *et al*., 2021). Contrastingly, Deutsch *et al*. (2008), Lister & Garcia (2018) and Soroye *et al*. (2020) deem climate change to be the major influencer. Although drivers can be exclusive to specific taxa (for example honeybee colony collapse disorder (VanEngelsdorp *et al*., 2009)), they are almost always interlinked, often with amplified consequences (Cardoso *et al*., 2020; Wagner *et al*., 2021a; Outhwaite *et al*., 2022).

There has been a recent spike in reporting on insect trends though they vastly differ in taxonomic, geographic, and temporal coverage. Sánchez-Bayo & Wyckhuys (2019)'s speculations that 40% of insect species could go extinct in the next few decades have been prominent in media and subsequent literature, though fundamental issues - particularly around the extrapolation of findings to a global scale - have been discussed (Simmons *et al*., 2019). Hallmann *et al*. (2017) reported an alarming 76% decline in flying insect biomass between 1989 and 2016 in Germany regardless of habitat type, weather, or land-use. A comparable decline (67%) was observed by Seibold *et al*. (2019) for arthropod biomass in German grasslands (2008-2017), along with a 34% decline in species richness, emphasising differences between biodiversity metrics. In the Netherlands, macro-moth and ground beetle biomass is estimated to have declined by 61% and 42%, respectively, over 27 years (Hallmann *et al*., 2020).

Certain studies have less severe, or even positive findings such as Biesmeijer *et al*. (2006), who found decreases in bee richness in 52% and 67% of British and Dutch cells, but also increases in 10% and 4%, respectively. Additionally, the UK showed no significant change in hoverfly richness, and more Dutch cells showed increases than decreases. Powney *et al*. (2019) also assessed wild bees and hoverflies in Great Britain (1980-2013) using occupancy models, finding decreases in a third of species, while a tenth increased. On a wider taxonomic scale, Outhwaite *et al*. (2020) reported a 5.5% increase in occupancy of terrestrial insects in the UK (1970-2015), although Van Klink *et al*. (2020) concluded an 11% decline in abundance per decade. The differences may arise from the different metrics used or Van Klink *et al*. (2020)'s wider geographical (41 countries) and temporal (1925-2018) coverage.

These papers are complemented by a number of others: declines in carabid beetles (Brooks *et al*., 2012; Homburg *et al*., 2019), butterflies (van Strien *et al*., 2019; Wepprich *et al*., 2019), and bumblebees (Soroye *et al*., 2020) have all been reported. Although most studies are conducted in westernised countries, Lister & Garcia (2018) observed sustained biomass declines across 10 major arthropod taxa in a Puerto Rican rainforest since 1976, while Gillespie *et al*. (2020) and Loboda *et al*. (2018) both report declines in muscid fly abundance in the Arctic (1996-2014).

The concrete conclusion that can be drawn is the apparent spatial, temporal, and taxonomic variation (Hudson *et al*., 2017; Wagner *et al*., 2021b). Ollerton *et al*. (2014) reports a shift from losing over 3 British pollinating species per decade in the 1920s to 1950s, to losing 0.98 from the 1960s. When comparing habitat types, UK carabid trends varied from 50% declines in northern moorland and western pasture, to 50% increases in southern downland. Furthermore, certain taxa were found to be stable in certain habitats, whilst declining elsewhere (Brooks *et al*., 2012).

It is widely agreed that ecological traits of species and nature of the threat influence population trends (Dirzo *et al*., 2014; De Palma *et al*., 2015; Habel *et al*., 2019; Cardoso *et al*., 2020). Grassland sites with more agricultural land surrounding them experienced larger declines in arthropod abundance (Seibold *et al*., 2019), potentially explained by species' dispersal ability in a fragmented habitat. Rare species are often reported as faring worse than common ones (Powney *et al*., 2019; Outhwaite *et al*., 2020), though this was only true for biomass - and not abundance – of ground beetles reported by Hallmann *et al*. (2020). Additionally, Loboda *et al*. (2018) highlighted that the number of common fly species also decreased during their study. Declines are also more frequently reported in species which are specialists (Biesmeijer *et al*., 2006; Boyes *et al*., 2019), small (Homburg *et al*., 2019), have a shorter flight season (De Palma *et al*., 2015), or are univoltine (Wepprich *et al*., 2019).

This vast evidence of variation counters exaggerated claims speculated by certain papers; not all insects are in decline (Boyes *et al*., 2019; Wagner *et al*., 2021b). Even if the overall trend is negative, the majority of studies report stable or positive trends for a proportion of taxa (Saunders *et al*., 2020; Wagner *et al*., 2021a). In sharp contrast to most studies, Crossley *et al*. (2020) failed to find evidence for any net decline of insect abundance and diversity across the US, though Welti *et al*. (2021) argue the use of unsuitable datasets mean these findings must be interpreted with caution.

Despite the increased reports on insect trends, invertebrates are still underrepresented in long-term biodiversity change studies compared to vertebrates (Outhwaite *et al*., 2020; Wagner *et al*., 2021b). We therefore need more long-term time series data, especially considering the high annual variation displayed by this group (Fox *et al*., 2019; Didham *et al*., 2020; Montgomery *et al*., 2020).

The geographic and taxonomic restrictiveness of current knowledge is another major limitation (Hallmann *et al*., 2017). A lack of data from the tropics where insect biodiversity is highest is of particular concern (Lister & Garcia, 2018). To date, most insects remain undescribed and of those identified, only a small proportion have been studied in any depth (Montgomery *et al*., 2020). Inadvertently, the increasing attention has resulted in more records being available for recent years (Powney *et al*., 2019), which confounds our ability to determine a historic baseline to which we should compare the current state of species, termed shifting baseline syndrome (van Strien *et al*., 2019; Didham *et al*., 2020).

A fundamental aim for future research should be to disentangle the drivers of these trends, specifically their geographical and taxonomic extent (Hallmann *et al*., 2017; Boyes *et al*., 2019). Additionally, researchers should publish findings of positive and stable trends alongside negative trends to ease publication bias and aid meta-analyses (Montgomery *et al*., 2020). It must also be recognised that many datasets remain unanalysed, or have not been utilised effectively (Outhwaite *et al*., 2020; Wagner *et al*., 2021b). It is possible to overcome issues by analysing trends across multiple studies (Cardoso *et al*., 2020), which is becoming increasingly achievable with the emergence of sophisticated analysis tools (Habel *et al*., 2019).

**References**

Biesmeijer, J. C., Roberts, S. P., Reemer, M., Ohlemuller, R., Edwards, M., Peeters, T., Schaffers, A., Potts, S. G., Kleukers, R. & Thomas, C. (2006) Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science.* 313 (5785), 351-354.

Boyes, D. H., Fox, R., Shortall, C. R. & Whittaker, R. J. (2019) Bucking the trend: the diversity of Anthropocene ‘winners’ among British moths. *Frontiers of Biogeography.* 11 (3).

Brooks, D. R., Bater, J. E., Clark, S. J., Monteith, D. T., Andrews, C., Corbett, S. J., Beaumont, D. A. & Chapman, J. W. (2012) Large carabid beetle declines in a United Kingdom monitoring network increases evidence for a widespread loss in insect biodiversity. *Journal of Applied Ecology.* 49 (5), 1009-1019.

Cardoso, P., Barton, P. S., Birkhofer, K., Chichorro, F., Deacon, C., Fartmann, T., Fukushima, C. S., Gaigher, R., Habel, J. C. & Hallmann, C. A. (2020) Scientists' warning to humanity on insect extinctions. *Biological conservation.* 242, 108426.

Crossley, M. S., Meier, A. R., Baldwin, E. M., Berry, L. L., Crenshaw, L. C., Hartman, G. L., Lagos-Kutz, D., Nichols, D. H., Patel, K. & Varriano, S. (2020) No net insect abundance and diversity declines across US Long Term Ecological Research sites. *Nature ecology & evolution.* 4 (10), 1368-1376.

De Palma, A., Kuhlmann, M., Roberts, S. P., Potts, S. G., Börger, L., Hudson, L. N., Lysenko, I., Newbold, T. & Purvis, A. (2015) Ecological traits affect the sensitivity of bees to land‐use pressures in E uropean agricultural landscapes. *Journal of Applied Ecology.* 52 (6), 1567-1577.

Deutsch, C. A., Tewksbury, J. J., Huey, R. B., Sheldon, K. S., Ghalambor, C. K., Haak, D. C. & Martin, P. R. (2008) Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences.* 105 (18), 6668-6672.

Dicks, L. V., Breeze, T. D., Ngo, H. T., Senapathi, D., An, J., Aizen, M. A., Basu, P., Buchori, D., Galetto, L. & Garibaldi, L. A. (2021) A global-scale expert assessment of drivers and risks associated with pollinator decline. *Nature ecology & evolution.* 5 (10), 1453-1461.

Didham, R. K., Basset, Y., Collins, C. M., Leather, S. R., Littlewood, N. A., Menz, M. H., Müller, J., Packer, L., Saunders, M. E. & Schönrogge, K. (2020) Interpreting insect declines: seven challenges and a way forward. *Insect Conservation and Diversity.* 13 (2), 103-114.

Dirzo, R., Young, H. S., Galetti, M., Ceballos, G., Isaac, N. J. & Collen, B. (2014) Defaunation in the Anthropocene. *Science.* 345 (6195), 401-406.

Fox, R., Harrower, C. A., Bell, J. R., Shortall, C. R., Middlebrook, I. & Wilson, R. J. (2019) Insect population trends and the IUCN Red List process. *Journal of Insect Conservation.* 23 (2), 269-278.

Gillespie, M. A., Alfredsson, M., Barrio, I. C., Bowden, J. J., Convey, P., Culler, L. E., Coulson, S. J., Krogh, P. H., Koltz, A. M. & Koponen, S. (2020) Status and trends of terrestrial arthropod abundance and diversity in the North Atlantic region of the Arctic. *Ambio.* 49 (3), 718-731.

Gray, C. L., Hill, S. L., Newbold, T., Hudson, L. N., Börger, L., Contu, S., Hoskins, A. J., Ferrier, S., Purvis, A. & Scharlemann, J. P. (2016) Local biodiversity is higher inside than outside terrestrial protected areas worldwide. *Nature communications.* 7 (1), 1-7.

Habel, J. C., Samways, M. J. & Schmitt, T. (2019) Mitigating the precipitous decline of terrestrial European insects: Requirements for a new strategy. *Biodiversity and Conservation.* 28 (6), 1343-1360.

Hallmann, C. A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H. & Hörren, T. (2017) More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PloS one.* 12 (10), e0185809.

Hallmann, C. A., Zeegers, T., van Klink, R., Vermeulen, R., van Wielink, P., Spijkers, H., van Deijk, J., van Steenis, W. & Jongejans, E. (2020) Declining abundance of beetles, moths and caddisflies in the Netherlands. *Insect Conservation and Diversity.* 13 (2), 127-139.

Homburg, K., Drees, C., Boutaud, E., Nolte, D., Schuett, W., Zumstein, P., von Ruschkowski, E. & Assmann, T. (2019) Where have all the beetles gone? Long‐term study reveals carabid species decline in a nature reserve in Northern Germany. *Insect Conservation and Diversity.* 12 (4), 268-277.

Hudson, L. N., Newbold, T., Contu, S., Hill, S. L., Lysenko, I., De Palma, A., Phillips, H. R., Alhusseini, T. I., Bedford, F. E. & Bennett, D. J. (2017) The database of the PREDICTS (projecting responses of ecological diversity in changing terrestrial systems) project. *Ecology and evolution.* 7 (1), 145-188.

Lister, B. C. & Garcia, A. (2018) Climate-driven declines in arthropod abundance restructure a rainforest food web. *Proceedings of the National Academy of Sciences.* 115 (44), E10397-E10406.

Loboda, S., Savage, J., Buddle, C. M., Schmidt, N. M. & Høye, T. T. (2018) Declining diversity and abundance of High Arctic fly assemblages over two decades of rapid climate warming. *Ecography.* 41 (2), 265-277.

Millard, J., Outhwaite, C. L., Kinnersley, R., Freeman, R., Gregory, R. D., Adedoja, O., Gavini, S., Kioko, E., Kuhlmann, M. & Ollerton, J. (2021) Global effects of land-use intensity on local pollinator biodiversity. *Nature communications.* 12 (1), 1-11.

Montgomery, G. A., Dunn, R. R., Fox, R., Jongejans, E., Leather, S. R., Saunders, M. E., Shortall, C. R., Tingley, M. W. & Wagner, D. L. (2020) Is the insect apocalypse upon us? How to find out. *Biological conservation.* 241, 108327.

Newbold, T., Hudson, L. N., Hill, S. L., Contu, S., Gray, C. L., Scharlemann, J. P., Börger, L., Phillips, H. R., Sheil, D. & Lysenko, I. (2016) Global patterns of terrestrial assemblage turnover within and among land uses. *Ecography.* 39 (12), 1151-1163.

Newbold, T., Hudson, L. N., Phillips, H. R., Hill, S. L., Contu, S., Lysenko, I., Blandon, A., Butchart, S. H., Booth, H. L. & Day, J. (2014) A global model of the response of tropical and sub-tropical forest biodiversity to anthropogenic pressures. *Proceedings of the Royal Society B: Biological Sciences.* 281 (1792), 20141371.

Ollerton, J., Erenler, H., Edwards, M. & Crockett, R. (2014) Extinctions of aculeate pollinators in Britain and the role of large-scale agricultural changes. *Science.* 346 (6215), 1360-1362.

Outhwaite, C., McCann, P. & Newbold, T. (2022) Agriculture and climate change reshape insect biodiversity worldwide. *Nature.*

Outhwaite, C. L., Gregory, R. D., Chandler, R. E., Collen, B. & Isaac, N. J. (2020) Complex long-term biodiversity change among invertebrates, bryophytes and lichens. *Nature ecology & evolution.* 4 (3), 384-392.

Powney, G. D., Carvell, C., Edwards, M., Morris, R. K., Roy, H. E., Woodcock, B. A. & Isaac, N. J. (2019) Widespread losses of pollinating insects in Britain. *Nature communications.* 10 (1), 1-6.

Sánchez-Bayo, F. & Wyckhuys, K. A. (2019) Worldwide decline of the entomofauna: A review of its drivers. *Biological conservation.* 232, 8-27.

Saunders, M. E., Janes, J. K. & O’Hanlon, J. C. (2020) Moving on from the insect apocalypse narrative: engaging with evidence-based insect conservation. *BioScience.* 70 (1), 80-89.

Seibold, S., Gossner, M. M., Simons, N. K., Blüthgen, N., Müller, J., Ambarlı, D., Ammer, C., Bauhus, J., Fischer, M. & Habel, J. C. (2019) Arthropod decline in grasslands and forests is associated with landscape-level drivers. *Nature.* 574 (7780), 671-674.

Simmons, B. I., Balmford, A., Bladon, A. J., Christie, A. P., De Palma, A., Dicks, L. V., Gallego‐Zamorano, J., Johnston, A., Martin, P. A. & Purvis, A. (2019) Worldwide insect declines: an important message, but interpret with caution. *Ecology and evolution.* 9 (7), 3678-3680.

Soroye, P., Newbold, T. & Kerr, J. (2020) Climate change contributes to widespread declines among bumble bees across continents. *Science.* 367 (6478), 685-688.

Van Klink, R., Bowler, D. E., Gongalsky, K. B., Swengel, A. B., Gentile, A. & Chase, J. M. (2020) Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. *Science.* 368 (6489), 417-420.

van Strien, A. J., van Swaay, C. A., van Strien-van Liempt, W. T., Poot, M. J. & WallisDeVries, M. F. (2019) Over a century of data reveal more than 80% decline in butterflies in the Netherlands. *Biological conservation.* 234, 116-122.

VanEngelsdorp, D., Evans, J. D., Saegerman, C., Mullin, C., Haubruge, E., Nguyen, B. K., Frazier, M., Frazier, J., Cox-Foster, D. & Chen, Y. (2009) Colony collapse disorder: a descriptive study. *PloS one.* 4 (8), e6481.

Wagner, D. L., Fox, R., Salcido, D. M. & Dyer, L. A. (2021a) A window to the world of global insect declines: Moth biodiversity trends are complex and heterogeneous. *Proceedings of the National Academy of Sciences.* 118 (2).

Wagner, D. L., Grames, E. M., Forister, M. L., Berenbaum, M. R. & Stopak, D. (2021b) Insect decline in the Anthropocene: Death by a thousand cuts. *Proceedings of the National Academy of Sciences.* 118 (2).

Welti, E. A., Joern, A., Ellison, A. M., Lightfoot, D. C., Record, S., Rodenhouse, N., Stanley, E. H. & Kaspari, M. (2021) Studies of insect temporal trends must account for the complex sampling histories inherent to many long-term monitoring efforts. *Nature ecology & evolution.* 5 (5), 589-591.

Wepprich, T., Adrion, J. R., Ries, L., Wiedmann, J. & Haddad, N. M. (2019) Butterfly abundance declines over 20 years of systematic monitoring in Ohio, USA. *PloS one.* 14 (7), e0216270.