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 and 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 and 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 and Garcia (2018); 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 and 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 and 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 and 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).

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