Intro

**Intro to insects – wider context**

* Most successful group
  + Cardoso, 2020 - Major branch of tree of life, most successful taxonomic group on our planet.
  + Homburg, 2019 - Insects are most diverse taxon on Earth in terms in species numbers (see ICUN stats table).
* Their functions/uses. Why are insects important? Why are we interested in insects?
  + Sanchez-Bayo - Lepidoptera: pollination, natural pest control, prey items. Hymenoptera: bees for pollination and economic value. Diptera: pollinators, natural enemies of agricultural pests. Coleoptera: pest control and recycling of organic matter. Hemiptera: true bugs. Orthoptera: grasshoppers, locusts, crickets. Odonata: dragonflies and damselflies. Control mosquitos and agricultural pests.
* What could we risk losing if nothing done?
  + Along with species, we also lose abundance, biomass, diversity, unique functions, traits, and services and end up with more homogenised communities and networks with weaker and fewer connections (Cardoso et al., 2020).
  + Over 75% of the crops examined by Klein et al. (2007) relied upon animal pollination.
  + There will be a high price to pay if declines continue, for example pollination has huge impacts on crop yields, and hence has high economic value (Habel et al., 2019).
  + The risks of insect losses — particularly pollinators — is a particular risk to the global south where a high proportion of insect-pollinated crops are grown, compared to highly industrialised areas of Europe (Dicks et al., 2021). This is a big risk when demand for food is at an all time high.
  + Loss of pollinators is likely to have serious ecological and economic consequences. Crop yields will suffer from lack of pollination, along with wild plants dependent on insect pollination, which could see the loss of undiscovered drugs (Vanbergen and Initiative, 2013).

**BUT understudied and particularly hard to study**

* Until recently – lots of focus on vertebrates – now more focus on invertebrates.
  + Additionally, invertebrates are still understudied compared to vertebrates (Wagner et al., 2021b).
  + Insects under-represented in large-scale BD trend studies (Outhwaite, 2020)
  + We cannot generalise results from studies on species other than invertebrates to invertebrates due to Lawton et al. (1998)’s findings that no one animal group could be used as a reliable predictor for change in species richness across a gradient of increasing disturbance of other groups.
  + Insects continue to be undervalued by researchers. Of the papers analysed by (Titley et al., 2017), an even split was found between papers reporting on vertebrates in invertebrates. This is a substantial difference to the proportions of species in existence where 95% are invertebrates. This lack of representation in the literature could result in a lack of funding for these so-called ‘unimportant’ species.
* Most are undescribed
  + (Stork, 2018) approximate there to be 5.5 million insects in existence, though only 1 million have been described.
  + Our lack of knowledge on the majority of species, many of which have not even been described (Montgomery et al., 2020).
  + We may be experiencing the sixth mass extinction in evolutionary history, though it is hard to determine how hard insects are being hit due to limited data. (Dirzo et al., 2014).
* Why understudied?
  + Maybe understudied because of Milicic 2021 expert elicitation findings - The main disadvantages of insects were identified as pest damage to crops and their impact as invasive species.
  + The lack of focus on insects in the past may be due to over-focus on the disadvantages of insects including agricultural pests, disease vectors, and general nuisances. The outweighing positive services including pollination, pest control, and nutrient cycling have been widely overlooked until recently (Eggleton, 2020).
  + Insect populations prove particularly hard to monitor due to their highly dynamic nature. High variation between years is very common, hence the need for long-term data sets to reduce the effects of yearly variation (Fox et al., 2019).
  + When assessing whether insect species met the threshold to be classified as threatened, varying the start year of trends in butterfly and moth species influence the number of species classified as such (Fox et al., 2019).
* Shifting baseline syndrome, lack of historic records
  + Outhwaite, 2020 - Need to consider shifting baseline syndrome
  + Shifting baseline phenomenon may be influencing our opinions on insect trends. It is hard to find solid evidence to counter this due to a lack of historical records of insect trends (Didham et al., 2020).
  + Furthermore, with a ten-fold increase in the number of studies published which include ‘insect decline’ from 200 to 2010, it is really the case that insects are declining alarmingly now, or that we are only just becoming aware of it (Eggleton, 2020)?
* Even with the increasing focus, some taxa are over-represented
  + There is a bias towards monitoring butterflies, dragonflies, bees, and moths, which limits the extent to which we can draw conclusions for the state of insects as a whole (Hallmann et al., 2020).
* And many studies still suffer from lack of data
  + Even now, studies are suffering from a lack of data. For example, (Wepprich et al., 2019) could not report on a fifth of regularly observed butterflies in Ohio due to this. For 81 species of butterfly in Ohio from 1996-2016, 3 times as many species had negative population trends compared to positive trends.
  + An alternative study approach is to collect expert knowledge. Though prone to subjectivity, this is especially useful when data are deficient and can provide fresh perspectives. However, even this study reported a high proportion of responses as unknown trend, highlighting how understudied this group are (Miličić et al., 2021).
  + High variation from year to year also affects the usefulness of short-term studies (Didham et al., 2020).

**Findings on insect declines so far. BUT lots of variation.**

* Has been an increase in papers and findings so far suggest overall decline – enough to warrant further investigation and action to mitigate these declines
  + There has been increasing focus on insects in recent years, with more records collected (Powney et al., 2019).
  + We have enough evidence that we need to do more to mitigate insect declines but we do not yet fully understand the extent and reasons (Montgomery et al., 2020).
* Big range in findings – e.g. from sanchez bayo and hallmann to crossley. Insect Armageddon to not all in decline.
  + Sánchez-Bayo and Wyckhuys (2019) estimate alarming rates of decline that they predict will lead to the extinction of 40% of the world’s insect species within a few decades.
    - Don’t actually say it – but basically did vote counting using 73 historical reports.
    - Simmons et al., 2019 highlight some key issues with the Sánchez-Bayo and Wyckhuys (2019) paper: their search strategy was biased towards finding studies which report insect declines due to [declin\*] being a requirement; the study findings cannot be extrapolated globally as they are based mainly on studies conducted in North America and Europe; and the threats identified are simply stated, rather than being statistically tested.
    - Saunders et al. (2020) argue Sanchez-Bayo and Wyckhuys paper was damaging due to geographical extrapolation of findings beyond the scope of the study, but has which nevertheless become prominent in the media and subsequent papers as evidence of an ‘Insect apocalypse’
  + Hallmann et al., 2017 observed a seasonal decline of 76% total flying insect biomass from 1989 to 2016 in Germany regardless of habitat type, and the changes could not be explained by weather, land use, or habitat characteristics.
  + It is also important to realise that not all insects are declining (Wagner et al., 2021b).
  + Saunders, 2020 - many studies focus on declines when in fact, it is rare that a study does not report stable or positive findings for a certain proportion of taxa.
  + Crossley et al. (2020) is one of the few studies to report no overall trend in insect abundance and diversity since 1970. The lack of an increase or decrease was consistent across insect feeding groups or the intensity of land-use based on data collected in 68 US long term ecological research sites.
    - Welti et al. (2021) highlight issues with Crossley et al. (2020) in that the results are flawed due to the researchers violating the assumption that records were collected consistently between datasets.
  + Outhwaite et al. (2020)’s findings that terrestrial insects increased in average occupancy by 5.5% in the UK from 1970 to 2015 go against findings of many studies.
  + One example of a paper which focuses on increasing species is the reporting of increasing British moths by Boyes et al. (2019). Nevertheless, though the researchers focused on the 51 species that increased in abundance ad occupancy, it cannot be ignored that the remaining moths of the 330 that had sufficient data, declined. Further, these trends may prove transient — the trends could reverse over time. However, this paper does well at highlighting that not all species are in decline.

**Geography, time, and taxonomy all contribute to the wide variation that has been observed in insects (Wagner et al., 2021b).**

**Geographic variation / restrictiveness**

* Three-quarters of UK carabids declined in Brooks et al. (2012) between 1994 and 2008, though there were marked difference between habitat types. 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.
* Powney, 2019 - habitat influenced the decline — 55% decrease in species associated with uplands, 12% increase in dominant crop pollinators.
* The use for land around more natural sites may influence the rate of decline. For example, in Seibold et al (2019), the researcher found that grassland sites surrounded by land with a higher proportion of agricultural land shower stronger declines. This could be due to dispersal ability of species being reduced in a fragmented habitat or effects of pesticide pollution.
* Habitat doesn’t always have an influence - Van Strien et al. (2019) report an overall 84% decline in butterflies in the Netherlands between 1890 and 2017. Declines were strong in all of grassland, woodland, and heathland.
* We currently do not have enough data to assume that patterns observed for Westernised countries — where most research has been focused — also applies to tropics where despite high insect biodiversity, long-term species-level data is deficient (Wagner et al., 2021b).
* Our knowledge of insect population trends in the tropics is severely limited (Lister and Garcia, 2018).
* So far, the geographical restrictiveness of studies to human-dominated landscapes mainly in western and northern Europe makes it hard to generalise how the strength of trends on a global scale (Montgomery et al., 2020).
* Papers outside of Europe/America:
  + In the Arctic where data spanning more than 10 years was available, Gillespie et al. (2020) found significant declines in 7 of the 14 species of muscid fly studied between 1996 and 2014. The researchers were unable to report on the majority of taxa due to insufficient data, though is good eg of paper not studying North America or Europe.
  + 16 species of muscid flies were monitored by Loboda et al. (2018) in Greenland between 1996 and 2014. The researchers found a significant decrease of 80% of total abundance, which affect abundant species as well as rare ones.

**Temporal variation**

* Powney, 2019 - All severe declines in bees occurred since 2007, whereas hoverflies have experienced sustained steady declines from 1987 to 2012.
* (Ollerton et al., 2014) used historical records to assess the extinction rate of bee and flower-visiting wasp species in Britain. They inferred that the greatest decline of nearly 3.5 species per decade in the 1920s to 1950s coincided with intensification of agricultural practice. Following this, roughly 0.98 species were loss per decade.

**Taxonomic variation**

* Must consider different taxa and different levels of taxa
* Different levels of taxa:
  + Different types of studies provide a range of perspectives — for example, studies that generalise across datasets provide necessary viewpoints of the general health status of insects, though likely overlook species-level trends that more focused studies may capture (Wagner et al., 2021b).
  + Van Klink et al. (2020) found an average 9% decline per decade of terrestrial insect abundance but an 11% increase in freshwater insects over 41 countries between 1925 and 2018 using a meta-analysis
    - Jähnig et al. (2021) criticise Van Klink et al. (2020) for disregarding that the differences in abundance and biomass do not take into account changes in community structure by the replacement of sensitive species with tolerant ones. Further, the non-randomly selected sites cannot be used to report global trends.
    - SO missing species level trends
  + Vs Powney et al. (2019) studied species-level trends of wild bees and hoverflies in the UK using occupancy models between 1980 and 2013. The results indicated that a third of species have decreased, a tenth have increased.
* Biesmeijer et al. (2006) found significant decreases in bee richness observed in 52% and 67% of British and Dutch cells, respectively. This was based on rarefaction methods applied before and after 1980. They also observed increased in 10% and 4%, respectively. Hoverflies showed no significant change in the UK, but increases in 34% and decreases in 17% of Dutch cells.
* Macro-moths, beetles, and caddisflies declined by 3.8, 5.0, and 9.2% in mean number of individuals, respectively from 1997-2017 in the Netherlands. Whereas true bugs were stable and mayflies had uncertainty surrounding their trend (Hallmann et al., 2020).



**Metric variation**

* Divergent patterns were found between abundance and biomass measures. For abundance, abundant ground beetles had steeper declines than rare ones. Contrastingly for biomass, rare species fared worse (Hallmann et al., 2020). These results demonstrate that a decline in biomass cannot be directly assumed as a corresponding decline in abundance.
* Based on more than a million arthropod records, Seibold et al (2019) generally observed decreases in Germany grassland and forest sites from 2008 to 2017. Biomass, abundance, and number of species declined by 67%, 78% and 34%, respectively in grasslands. In forests, biomass and species number—but not abundance—decreased by 41% and 36%, respectively. These number demonstrate the big difference in results observed based on the metric used.
* (Homburg et al., 2019) did not observe a decline in abundance or biomass, but in species richness, functional diversity and phylogenetic diversity of carabids in Germany over 24 years. Homburg et al. (2019) observed smaller species to have stronger declines. This could explain why an overall decline in species richness, but not biomass, was observed.
* Depends on your goals as to which metric to use e.g. For pollination services, the abundance of species, rather than species richness, may be more important in the continuation of this service (Loboda et al., 2018).
* Hillebrand et al. (2018) highlight the important differences between the use of different biodiversity metrics and why we should proceed with caution when reporting on trends using just one metric. Species richness alone cannot reflect changes in community composition, thus masking changes in species identity and functional traits. It could be therefore be concluded that the population is stable, when in fact there has been complete species turnover.

**Threats to insects are particularly not understood.**

* Habitat loss and fragmentation, pollution, invasive species, climate change, over-exploitation, often acting synergistically (Cardoso et al., 2020). But there is still much to be understood.
* Alien species outcompete native insect for resources and can additionally spread pests and diseases. Honey bees particularly suffer from pest and diseases (Vanbergen and Initiative, 2013).
* The most important drivers of insect trends according to experts in (Miličić et al., 2021)’s expert elicitation study were agriculture and climate change.
* It is human-caused changes that are driving the observed declines (Eggleton, 2020).
* Honey bees are known to suffer from colony collapse disorder, which involves the loss of worker bees. No single driver is thought to be responsible, though pathogens appear to play a major role (VanEngelsdorp et al., 2009).
* Type and intensity

**Land-use / agriculture**

* Agricultural expansion and intensification leads to large areas of monoculture, which although can provide a resource for pollinators, the crops are often characterised by short periods of flowering, which is inadequate for pollinators with longer flight seasons (Vanbergen and Initiative, 2013).
* From an expert elicitation process, Dicks et al. (2021) concluded land cover and configuration, land management and pesticides to be the main drivers of insect declines.
  + Expert elicitations are good when data is deficient and could gleam additional insights, though it is subjective due to its basis in personal opinions.
* (Newbold et al., 2014) used PREDICTS data to study how land-use affects biodiversity of invertebrates, ‘herptiles’ (reptiles and amphibians), mammals and birds in tropical forests. Land-use significantly impacted the probability of occurrence of species, with declines in human-modified habitats. These habitats also consisted of dominance by fewer species.
* It has been shown that land-use can have varying effects depending on location. For example, land-use has a greater effect on beta diversity in tropical compared to temperate regions (Newbold et al., 2016b).
* Newbold et al. (2018) report that land-use change is causing a shift to more widespread species, and thus resulting in a homogenisation. This was true for plants and vertebrates, as well as invertebrates using the PREDICTS database records.
* Generally, intensification of land-use is associated with decreases in biodiversity. However, this is not true in every case. For pollinators, Millard et al. (2021) found species richness and total abundance in non-tropical cropland was significantly higher in minimal-intensity than primary-vegetation. This was in contrast to the decrease seen between primary vegetation and high intensity crop land in tropical areas. These differences could stem from non-tropical areas having a longer history of agriculture, meaning sensitive species have previously gone extinct. These extinctions could still happen in tropical regions, but extinction-debt effects may be inhibiting detection.
* Temperature preference and habitat specificity both impacted the trends observed, with the former being most significant. Species with higher temperature preferences increased the most in occupancy across all taxa. Butterfly habitat specialists decreased across the study period, but the same was not true for grasshoppers and dragonflies. This may be due to butterflies possessing a higher proportion of specialised taxa, the existence of which are associated with high quality habitats. These results indicate land-use as a potential driver which particularly affects the butterfly taxa (Engelhardt et al., 2022).

**Climate change**

* Climate change affects intrinsic rates of population growth. It is predicted that tropical insects will suffer more due to the warming tolerance of tropical insects being, on average, a fifth of that of higher-latitude insects. This makes tropical insects particularly sensitive to increases in temperature, especially considering they are currently living close to their thermal optimum. It is also especially concerning seeing as biodiversity is greatest in the tropics (Deutsch et al., 2008).
* Climate change is likely to lead to differential rates of migration by plants and insects leading to a mismatch between species which rely on one another (Vanbergen and Initiative, 2013).
* Climate affects species by changing environmental conditions so the temperature exceeds the tolerance of a species, causing extinction or range shifts, or making new areas more suitable for survival. Climate change not only directly affects bumblebees by affecting fecundity and mortality, but also indirectly through alteration to floral resource. Soroye et al. (2020)
* (Lister and Garcia, 2018) report sustained biomass declines across all 10 major taxa in a Puerto Rican rainforest between 1976 and 2012. As average ambient temperature was found as a significant predictor of abundance, the authors believe it is climate warming causing these declines. The authors disregard theories that the warming is caused by land-use change — for example, clearing of the rainforest increasing surface temperature — because the rainforest has not undergone significant human disturbance during the study period. Further, the authors also note that range shifts could play a role, though this was not investigated.
  + (Willig et al., 2019) replicate some of the analysis performed by Lister and Garcia (2018), concluding completely contrasting results. They report no evidence that declines are occurring due to climate warming. This could be due to Lister and Garcia (2018) failing to account for effects such as droughts and hurricanes in addition to temperature related aspects of climate change. Further, abundance data was not adjusted according to sampling effort, which could lead to erroneous results.
* Soroye et al. (2020) point to climate change as the main driver of bumblebee declines they found across North America and Europe. Increasing occurrence of hotter temperatures was able to predict extinction risk and chance of colonisation.
* At species level, most climate predictors could not explain the trend of decline of muscid flies in Loboda’s (2018) study.
* Van Klink et al. (2020) found no association between climate change and insect population trends, either at local or regional scale.

**Other**

* Interactions
  + (Outhwaite et al., 2022) report on the importance of the interaction between land-use change and climate change on impacting insect population trends. Using PREDICTS data from 1992 to 2012, the researchers found that an increase of 1 standard deviation from the baseline temperature in high-intensity agriculture reduced abundance and richness by 49 and 27%, respectively, compared to primary vegetation with no warming. The equivalent figures for low-intensity agriculture were 30 and 23%, respectively. The results indicate that less intensive agriculture partially buffers insects against the negative impacts of climate warming.
* Future work aims
  + Nearly half of the studies reviewed by Sánchez-Bayo and Wyckhuys (2019) indicated habitat change to be the largest contributor to insect declines. BUT not actually properly tested.
  + Hallmann, 2020 - Identifying causes of decline was beyond the scope of the study.
  + Researchers often speculate reasons for decline rather than empirically investigating the drivers. For example, Homburg et al. (2019) assume climate change and pollution to cause the observed declines, but do not include this in their study design.
  + A major aim for future work is to investigate the causes of the decline, and where they have the biggest impact (Hallmann et al., 2017).
  + A major aim for future work is to investigate the causes of the decline, especially where they have the biggest impact, and any possible interactions (Wagner et al., 2021b).
  + Outhwaite, 2020 - Determining drivers will aid mitigation of future losses.
  + Future work should focus on determining the full effects of drivers, which is increasingly possible using large data sets and modern analysis tools (Habel et al., 2019).
  + There is an urgent need for more data to untangle the geographical and temporal effects of drivers, and identify examples where the drivers interact (Wagner et al., 2021a).

**Neither are species traits**

* Specialist vs generalist
  + Biesmeijer, 2006 - Declines were more frequent in habitat/food specialists
  + The majority of the increasing moth species were generalists (Boyes et al., 2019).
  + Wagner, 2021a - Habitat and dietary specialists show stronger rates of decline than generalists.
  + Of the species which declines, common and invasive species were also affected. (Wepprich et al., 2019).
* Rare vs common
  + Powney, 2019 - Rare species fared worse
  + Outhwaite, 2020 - Rare species show greater change
  + We tend to see specialist, rare species faring worse than common species, though it has been highlighted that this could be due to rarer species being harder to monitor. If common species are also declining, this could have much stronger impacts on ecosystem functioning (Cardoso et al., 2020).
* Dispersal ability
  + Traits are extremely important for inclusion in future studies to determine the traits that increase extinction risk. So far, it is believed that poor dispersers are particularly prone to extinction (Cardoso et al., 2020).
* Univoltine
  + Biesmeijer, 2006 - Declines were more frequent in univoltine species
  + Univoltine species were more strongly negatively affected (Wepprich et al., 2019).
* Flight season duration and foraging range
  + It is useful to understand which traits have most impact on insect population trends. De Palma et al. (2015) studied 257 European bee species, concluding that flight season duration was the most important trait for predicting sensitivity to land-use, with foraging range also playing a role. This may be due to shorter flight seasons being more likely to lead to a mismatch between flowering time and presence of pollinator.
  + Larger foraging range may affect insect population trends positively by allowing resource availability in a fragmented habitat — it could also mean a higher risk of pesticide exposure (De Palma et al., 2015).
  + It has been shown that the interaction between species attributes and land-use is important, with (De Palma et al., 2015)’s models which excluded interactions explaining 13% and 37% less variation in occurrence and abundance of bees, respectively.
* Size
  + Homburg (2019) investigate which species traits influence trends, concluding smaller body size to be particularly important.
* Study survival as well as extinction traits
  + Nevertheless, the increase in some adaptable, generalist species cannot be ignored (Sánchez-Bayo and Wyckhuys, 2019) and should be studied to observe traits that contribute to survival despite the increasing threats.
  + The traits that mean species survive may be as important to identify as those which lead species to decline (Boyes et al., 2019).
* More complicated due to interactions
  + There appears to be differences in how rare and abundant species react depending on habitat type. In grasslands, declines were mainly observed in rare species, whereas in forests, both rare and abundant species were affected (Seibold et al., 2019).

**Lots of datasets not analysed or utilised effectively – need way of doing this.**

* Future papers should also report stable or positive trends, to ease publication bias and improve meta-analyses (Montgomery et al., 2020).
* (Engelhardt et al., 2022)’s study highlight the importance of best utilising existing datasets, rather than having the expend additional resources on new data collection.
* Now have enough meta-analyses to start doing meta-meta-analyses.
* Also, relatively new idea.
* But need effective way of bringing large amounts of data together and visualising results. Results such as this are difficult to visualise, interpret, and explain. No widely available tool exists.
* Furthermore, many datasets in existence remain unanalysed (Wagner et al., 2021b). Therefore, there is a need to develop new pipelines that will best utilise these.
* It is important that future research makes best use of existing data by analysing it with up-and-coming research methods (Outhwaite et al., 2020).

**Introduce shiny app. Here, I present….**

* My shiny app fills this gap (careful with taking these words as they are from other papers). Good for persuading public, and policy/decision makers.
* My shiny app allows…
* Reactive to changes as more data is added to the dataset.
* Open-source?