A global-scale expert assessment of drivers and risks associated with pollinator decline

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Pollinator decline has attracted global attention, and substantial efforts are underway to respond through national pollinator strategies and action plans. These policy responses require clarity on what is driving pollinator decline, and what risks it generates for society, in different parts of the world. Using a formal expert elicitation process, we evaluated the relative regional and global importance of eight drivers of pollinator decline, and ten consequent risks to human well-being. Our results indicate that global policy responses should focus on reducing pressure from changes in land cover and configuration, land management, and pesticides, as these were considered very important drivers in most regions. We quantify how the importance of drivers, and risks from pollinator decline, differ among regions. For example, losing access to managed pollinators was considered a serious risk only for people in North America, whereas yield instability in pollinator-dependent crops was classed as a serious or high risk in four regions, but only a moderate risk in Europe and North America. Overall, perceived risks were substantially higher in the Global South. Despite extensive research on pollinator decline, our analysis reveals considerable scientific uncertainty about what this means for human society.

Main text

Animal pollination is key to the reproductive success of >75% of flowering plants globally, including many culturally and economically significant plants[1,2]. Pollination services are estimated to add billions of dollars to global crop productivity and contribute significantly to nutritional security[3]. Despite these multiple values, there is growing evidence of wild pollinator population declines[4,5] and deficits in crop production due to insufficient pollination[6], while global demand for pollination services is at an all-time high[7] and likely to continue to grow[8]. Conversely, populations of managed honey bees, while declining in North America and parts of Europe, are increasing in many countries[9]. Observed trends in wild pollinators have been mostly linked with changes in land management[10], climate change[11], and agrochemical use[12], although these analyses are largely restricted to Europe and North America. Restoring or diversifying habitats and reducing management pressures such as pesticides and grazing have been shown to positively affect wild pollinator populations and managed honey bee health[13-15].

In response to evidence of declines, pollinators and pollination have attracted public and policy attention globally[2,16], and substantial efforts are underway to respond, through national pollinator strategies and action plans[17]. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) performed a global assessment of pollinators, pollination and food production from 2014-2016[1]. This underpinned the adoption of new commitments to support pollinator conservation by signatories to the Convention on Biological Diversity[18] and subsequent steps towards developing national pollinator strategies and action plans in many nations[17]. One clear message from the pollination assessment was that evidence on the status and trends in pollinator populations, threats, and the impacts of their decline, is concentrated in high-income countries, rather than regions thought to be most vulnerable to decreases in pollinator diversity[19] and pollination services[20]. However, unlike the more recent IPBES global assessment on biodiversity and ecosystem services[21], the pollination assessment did not directly compare and rank the relative importance of major drivers of pollinator decline, or make any integrated assessment of the risks it generates for society, either at global or regional levels. Consequently, although researchers have made broad, global recommendations about how to respond to pollinator decline[16], addressing specific drivers and risks at national or regional scales appropriate for policy implementation has been more challenging[22].

Here, we used a structured expert elicitation technique and a globally representative group of 20 pollinator and pollination experts, all authors of this paper, to evaluate the relative importance of eight major direct drivers (or causes) of observed pollinator decline, and the risks to human well-being associated with ten direct impacts of pollinator decline defined by the IPBES report[1] (Tables 1 & 2; Supplementary Table 1). We separately assessed each of six global continental regions, with the exceptions that, for biogeographic and geopolitical reasons, the Pacific islands were grouped with Asia (Asia-Pacific) and not with Australia and New Zealand, while MesoAmerica and the Caribbean were grouped with South America into Latin America (see Methods; Figure S1). We did not assess indirect impacts, such as increased land conversion in response to lower crop yields. Nor did we consider interactions between multiple drivers, despite their likely influence on pollinator decline[2], because knowledge about driver interactions remains largely incomplete and insufficient for the scale and scope of analysis here.

Understanding and communicating risks to human well-being associated with biodiversity loss play a central role in raising awareness of our dependence on nature, and in driving the transformative societal change required to conserve and restore biodiversity worldwide[23]. We take a scientific-technical approach, in which a risk is understood as the probability of a specific hazard or impact taking place. We used a semi-quantitative risk matrix, with risk scores calculated as the product of probability, scale and severity of impacts, and a ‘four-box model’ established by the IPBES (Figure 1, Table 2) to communicate levels of confidence[1], thus highlighting the key known ‘unknowns’ in current scientific understanding. Our assessment used a modified Delphi technique[24], an approach designed to reduce bias, but particularly suitable for elicitation of expert judgements about complex issues, where the judgement requires a range of different perspectives and areas of expertise not necessarily held by each participant[24].

Results

What's driving pollinator declines?

Figure 2 shows final scores for the importance of the six drivers defined in Table 1, following three rounds of scoring. Globally, land cover and configuration, and land management were the most important drivers of pollinator declines (Figure 2; Supplementary Tables 2 & 4). Land cover and configuration was scored 'very important' in all six regions, while land management was the only variable considered to be 'the most important' in any region (Europe) and was 'very important' in all other regions except Africa (Figure 2). These conclusions are supported by considerable evidence from multiple regions[25-27] and continuing global trends towards agricultural expansion, conventional intensification, and urbanization in regions of the Global South, driven by international trade[28]. Land management was considered less important in Africa, where access to the necessary financial and technical capital to intensify production is still limited[29] and where there was considerable uncertainty (categorised as 'inconclusive') over the influence of land cover and configuration (Figure 2).

Pesticides were scored as 'important' or 'very important' drivers of pollinator decline in all regions, with the greatest confidence in Latin America and Asia/Pacific (Figure 2). Pesticides were considered less important than land management in Europe and Australia/New Zealand, but much more important in Africa (Figure 2). The adverse effects of pesticides on pollinators have received considerable attention in recent years, following studies demonstrating widespread exposure[30] and detrimental effects on populations[31,32] or diversity[27]. There is far less evidence available to quantify the exposure in regions beyond Europe and North America. Also, despite very rapid increases in pesticide use since 1990 in middle income countries of Africa, Latin America and Asia-Pacific[33], pesticide regulations are weaker in the Global South, adding considerably to the risk[1,33,34].

Climate change was considered an ‘important’ or ‘very important’ driver in every region. There was, however, unanimous lack of confidence over its importance relative to other drivers. In every region except Africa, median confidence scores were ‘medium’ and in Africa, seven of the ten scorers responded that climate change effects are ‘unknown’ (Exended Data Figure 2 and Supplementary Table 2). Long-term data scarcity limit and confound the demonstration of current climate change effects on pollinators, and available studies are restricted to few taxa such as bumblebees[11] and butterflies[35].

Genetically modified organisms (GMOs) were considered the least important driver overall, except in Latin America (Figure 2), which is the second largest producer of GM crops among our regions, after North America[36]. Emerging evidence of potential impacts of herbicide-tolerant crops and associated glyphosate use on honey bees was discussed in the Latin American context (now reviewed[37]). Levels of confidence and agreement were lower overall for GMOs and invasive alien species as drivers of pollinator decline, due to very limited available evidence. In the case of GMOs, impacts on pollinators vary according to the type of GM crop[2], and are difficult to separate from the effects of land cover and configuration, because such crops are often produced in large monocultures.

What are the risks to human well-being?

Figure 3 shows the final risk scores following three rounds of scoring, partitioned into probability and magnitude (scale × severity), for each of the direct impacts listed in Table 2, in each major global region. Overall, loss of wild pollinator diversity and crop pollination deficit were the highest and most widespread risks, scoring as serious or high risks in every region (see Figure 3, Supplementary Tables 3 & 7). Although much of the published evidence for pollinator declines is from Europe and North America (where the evidence was considered ‘well established’)[2], there is growing evidence of pollinator declines in other regions[19,38], including vertebrate pollinators[39], along with global evidence of general biodiversity decline[23]. Evidence for pollination deficits is also growing across several regions[6,40-42] (Figure 3), although for Australia/NZ and Africa, the degree of confidence was 'inconclusive', indicating low amounts of evidence and low agreement among our experts (see Table 3 for definitions). This is a particular concern in Africa and Asia-Pacific, where pollinated crops are of noteable nutritional[3] and economic[43] value to livelihoods and well-being. Yield instability in pollinator-dependent crops, which is higher than that for non-dependent crops at global scale[44], was classed as a serious or high risk in four of the six regions but moderate in Europe and North America, where highly pollinator dependent crops tend to be less widely grown and less important to total agricultural output. Direct impacts of wild fruit production losses had very low risk scores in economically developed regions of North America, Europe and Australia/New Zealand (median scores <6), but classed as a serious risk in Africa, Asia-Pacific and Latin America (Figure 3). These regions are dominated by low- to middle-income countries, where at least for Africa and Asia-Pacific, large portions of the population live in rural communities[45].

Risks were greatest in Latin America compared to other regions (Supplementary Table 3: mean risk score across all ten impacts = 48.2), with four 'high' risks (pollination deficits, yield instability, food system resilience and wild pollinator diversity) and five 'serious' risks (all others except managed pollinators). This reflects the high diversity of insect pollinated crops grown and exported throughout the region, often by smallholder farmers in and around areas of natural habitats that contain a high diversity of pollinating insects[46]. Continuing losses of pollinators are therefore likely to destabilise both regional food production and international trade, affecting livelihoods across the region. Like other regions of the Global South, Latin America is also home to a high diversity of extant indigenous cultures and people, many of whom rely on subsistence agriculture and natural resources such as nontimber forest products[47], increasing the risks from a decline in honey, wild fruits, and cultural values.

In contrast to Latin America, Africa had very low risk scores for honey production and managed pollinators (both ‘low’ risk; see Figure 3 and Supplementary Table 3). Beekeeping is unique in Africa since it is the only global region that has large, genetically diverse populations of native honey bees (*Apis mellifera*, various subspecies) still thriving in the wild[48]. In fact, numbers of managed hives are increasing in many African countries due to limited colony losses and managed honey bee populations relatively resilient to *Varroa* mite[49].

The risk of loss of aesthetic values, happiness, or well-being associated with wild pollinators or wild plants dependent on pollinators was perhaps the most difficult to score in all regions. In some contexts, one can make an argument that aesthetic values associated with pollinators are increasing, as people become more aware of their roles, beauty, and diversity. Discussions focused on what constitutes aesthetic values and how they might be changing in response to pollinator decline (Supplementary Table 11). This risk varied regionally, with Latin America and Africa scored highest (42) and lowest (4) risk, respectively (Fig. 3, Supplementary Table 3). While clear links exist between people and pollinators or pollinator-dependent plants in both regions, for Latin America, these links are often related to specific threatened taxa, such as hummingbirds and orchids. In Africa, connections with pollinator-dependent plants are frequently associated with entire landscapes, such as the flower-rich shrubland of Namaqualand, southern Africa, making potential impacts of pollinator decline on aesthetic values less clear (see Supplementary Table 11).

Europe was the region where human well-being was considered at the lowest risk from pollinator declines overall (mean risk score = 19.6), with no ‘high’ risks, and only two ‘serious’ risks (pollination deficit and wild pollinator diversity). Unlike Latin America, many European countries grow relatively few crops that are highly pollinator dependent and food systems, particularly within the European Union, are highly industrialised and globalised, greatly reducing the importance of wild fruits and buffering against the impacts of global change on food system resilience (both ‘low’ risk). Despite evidence that habitats containing pollinator-dependent plants are aesthetically valued in Europe[50], their cultural importance may be lower than elsewhere in the world, although this was highly uncertain, with our risk score for ‘cultural values’ in Europe categorised as ‘inconclusive’ due to low confidence and low agreement among scorers.

Loss of access to managed pollinators was only considered a serious risk to people in North America, where honey bees *A. mellifera* represent a key input to large scale, industrialised cropping systems such as almond[51], and have suffered serious declines in the past due to outbreaks of disease, pests and ‘colony collapse disorder’[52]. The probability of the same occurring in say, Latin America or Asia-Pacific, was considered far lower, even if the severity of the impact would be similar (Figure 3, Supplementary Table 3). Experts were divided (low agreement) on the risk from losing managed pollinators in Europe (Figure 3), where markets for pollination services are less well developed than in North America[53], and Latin America, where the number of managed honey bee colonies has expanded substantially but pressures on their populations remain high[7].

Across both risks and drivers, there was high agreement but low confidence for most factors, placing them in the ‘established but incomplete’ confidence category. Our confidence in several direct impacts was low because of numerous gaps in knowledge about the ecology and status of all but the most common pollinator species, and the relationships between pollinators, human economies, and culture[20,54]. Furthermore, while statistical information on crop production, managed pollinators, and honey production is often collected at a national scale, the quality of these data varies considerably within a region and over time, and does not capture subsistence agriculture, particularly in the Global South.

Discussion

In our analysis, the global ranking of drivers of pollinator decline by importance (Figure 2) differs from the order of relative impact of direct causes of biodiversity loss (or ‘changes in the fabric of life’) presented by Díaz et al, based on the IPBES global assessment[23]. In both cases, land use change (here, land cover and configuration) for terrestrial realms is the most important driver, but for the whole of nature[23], ‘direct exploitation’ is the next most important driver, followed by climate change, pollution and invasive alien species. For pollinators, direct exploitation is broadly equivalent to ‘Pollinator management’ (not including direct harvesting of pollinators or pollinator products, which is not suggested as a major driver of pollinator decline). This was ranked with lower importance than climate change, pesticides, and pests and pathogens in our assessment. For pollinators, climate change was ranked below pesticides as a driver, perhaps reflecting more complete evidence that current pesticide use negatively impacts pollinator populations[12,31], through a range of lethal and sublethal effects. Climate change impacts on pollinators are likely to be longer term. Much of the current evidence shows shifting ranges, which only sometimes translate into population declines[11], or highly uncertain projected future distributions under climate change. Although these two analyses used different methods for ranking drivers (Díaz et al[23] quantified the relative impact of each driver, based on rankings in published studies comparing two or more drivers), it is not surprising that the relative importance of drivers differs, when focusing on a functionally defined subset of organisms (pollinators) that are almost all relatively small in size.

Despite high profile, extensive research on the drivers and impacts of pollinator decline, our analysis reveals considerable scientific uncertainty about what this means for human society, regionally and globally. There are clear risks of wild pollinator diversity loss and crop pollination deficits globally, yet less is understood about the broader implications for human well-being. The case for action to address pollinator decline is most clearly made for Latin America (Figure 3).

We followed an explicit, transparent and systematic process of risk assessment, as recommended by Zommers *et al.*[55] for robust climate change risk assessment. Even so, a number of limitations to this approach have been clearly defined[56,57]. Perhaps the most pertinent here is the potential for our results to be influenced by the value judgements and world views of our individual experts. For example, when rating 'severity' of impacts, people whose lives are directly affected might be inclined to rate severity more highly than those unaffected. When rating 'probability', interpretation of verbal scales by individual experts can be poorly aligned or even overlap, when measured again numerical scales; in extreme cases, what is 'likely' to one person can be considered 'unlikely' by another [58]. One way to reduce this subjectivity would be to define explicit, sharp or fuzzy boundaries for the categories in our verbally described scales (Supplementary Table 1), using specified numerical scales, thereby reducing 'vagueness'[59]. Several underlying numerical scales can be conceptualised for all the elements of risk we assessed. Possible scales could be derived from available data on the impacts themselves over time or space (for probability), the numbers or proportions of people who could be affected (for scale), and contributions to health, well-being and income from particular activities (for severity). For example, to judge the probability of a fall in honey production, we discussed the relevance and quality of available data on honey production and numbers of managed honey bee hives[60], and the trends shown by these datasets, for each region. To judge the scale of impact of a fall in honey production in terms of numbers of people affected, we considered numbers of beekeepers, honey hunters and honey consumers, across each region. To judge the severity of this impact, we considered the proportions of beekeepers', farmers' and honey hunters' incomes that come from honey, and the relative impacts of honey on people's individual health outcomes (see Supplementary Table 11). However, for most of our impacts, numerical data were available only for a small proportion of the issues considered, in a subset of possible contexts and usually not at regional scale, so using numerically specified boundaries would still have demanded subjective judgements or speculation. In these circumstances, providing numerical scales to delineate the categories would represent an unfounded and misleading level of precision.

Our process reveals several major knowledge gaps. There is an urgent need for research in Africa[61], to address the substantial uncertainties around the risks to people from pollination deficits (Figure 3), and the importance of changes in land cover and configuration, as a driver of pollinator decline (Figure 2). In more developed regions, especially North America, we lack understanding of the scale and severity of impacts of pollinator decline on human well-being (Supplementary Table 3). Globally, the consequences of climate change for pollinators and pollination remain poorly understood, but its impacts will clearly increase in prominence in the coming decades[23]. As climate change is very likely to interact with other drivers of pollinator decline, a focus on how to mitigate and adapt to it should be central to pollinator research and conservation strategies.

References

1 IPBES. The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. (Bonn, Germany, 2016).

2 Potts, S. G. *et al.* Safeguarding pollinators and their values to human well-being. *Nature* **540**, 220-229, doi:10.1038/nature20588 (2016).

3 Chaplin-Kramer, R. *et al.* Global malnutrition overlaps with pollinator-dependent micronutrient production. *Proceedings of the Royal Society B: Biological Sciences* **281**, doi:10.1098/rspb.2014.1799 (2014).

4 Powney, G. D. *et al.* Widespread losses of pollinating insects in Britain. *Nat Comm* **10**, 1018, doi:10.1038/s41467-019-08974-9 (2019).

5 Koh, I. *et al.* Modeling the status, trends, and impacts of wild bee abundance in the United States. *PNAS* **113**, 140-145, doi:10.1073/pnas.1517685113 (2016).

6 Reilly, J. R. *et al.* Crop production in the USA is frequently limited by a lack of pollinators. *Proceedings of the Royal Society B: Biological Sciences* **287**, 20200922, doi:10.1098/rspb.2020.0922 (2020).

7 Aizen, M. A. *et al.* Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. *Global Change Biol* **25**, 3516-3527, doi:10.1111/gcb.14736 (2019).

8 Chaplin-Kramer, R. *et al.* Global modeling of nature's contributions to people. *Science* **366**, 255-+, doi:10.1126/science.aaw3372 (2019).

9 Moritz, R. F. A. & Erler, S. Lost colonies found in a data mine: Global honey trade but not pests or pesticides as a major cause of regional honeybee colony declines. *Agriculture, Ecosystems & Environment* **216**, 44-50, doi:https://doi.org/10.1016/j.agee.2015.09.027 (2016).

10 Senapathi, D., Goddard, M. A., Kunin, W. E. & Baldock, K. C. R. Landscape impacts on pollinator communities in temperate systems: evidence and knowledge gaps. *Funct. Ecol.* **31**, 26-37, doi:10.1111/1365-2435.12809 (2017).

11 Soroye, P., Newbold, T. & Kerr, J. Climate change contributes to widespread declines among bumble bees across continents. *Science* **367**, 685, doi:10.1126/science.aax8591 (2020).

12 Woodcock, B. A. *et al.* Country-specific effects of neonicotinoid pesticides on honey bees and wild bees. *Science* **356**, 1393-1395, doi:10.1126/science.aaa1190 (2017).

13 Carvell, C. *et al.* Bumblebee family lineage survival is enhanced in high-quality landscapes. *Nature* **543**, 547, (2017).

14 Tonietto Rebecca, K. & Larkin Daniel, J. Habitat restoration benefits wild bees: A meta-analysis. *Journal of Applied Ecology* **55**, 582-590, doi:10.1111/1365-2664.13012 (2017).

15 Wintermantel, D., Odoux, J.-F., Chadœuf, J. & Bretagnolle, V. Organic farming positively affects honeybee colonies in a flower-poor period in agricultural landscapes. *J Appl Ecol* **56**, 1960-1969, doi:10.1111/1365-2664.13447 (2019).

16 Dicks, L. V. *et al.* Ten policies for pollinators. *Science* **354**, 975-976, (2016).

17 Food and Agriculture Organization of the United Nations. *FAO's Global Action on Pollination Services for Sustainable Agriculture: National Initiatives*, http://www.fao.org/pollination/major-initiatives/national-initiatives/en/ (2020).

18 Convention on Biological Diversity. 14/6. Conservation and sustainable use of pollinators Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity. (CBD/COP/DEC/14/6 30 November 2018, 2018).

19 Teichroew, J. L. *et al.* Is China's unparalleled and understudied bee diversity at risk? *Biol Cons* **210**, 19-28, doi:10.1016/j.biocon.2016.05.023 (2017).

20 Breeze, T. D., Gallai, N., Garibaldi, L. A. & Li, X. S. Economic Measures of Pollination Services: Shortcomings and Future Directions. *TREE* **31**, 927-939, doi:10.1016/j.tree.2016.09.002 (2016).

21 IPBES. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondizio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). (IPBES secretariat, Bonn, Germany, 2019).

22 Hall, D. M. & Steiner, R. Insect pollinator conservation policy innovations at subnational levels: Lessons for lawmakers. *Environmental Science & Policy* **93**, 118-128, doi:https://doi.org/10.1016/j.envsci.2018.12.026 (2019).

23 Díaz, S. *et al.* Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* **366**, eaax3100, doi:10.1126/science.aax3100 (2019).

24 Mukherjee, N. *et al.* The Delphi technique in ecology and biological conservation: applications and guidelines. *Methods Ecol Evol* **6**, 1097-1109, doi:10.1111/2041-210X.12387 (2015).

25 Kovács-Hostyánszki, A. *et al.* Ecological intensification to mitigate impacts of conventional intensive land use on pollinators and pollination. *Ecol Lett* **20**, 673-689, doi:10.1111/ele.12762 (2017).

26 Kennedy, C. M. *et al.* A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecology Letters* **16**, 584-599, doi:Doi 10.1111/Ele.12082 (2013).

27 Basu, P. *et al.* Scale dependent drivers of wild bee diversity in tropical heterogeneous agricultural landscapes. *Ecol Evol* **6**, 6983-6992, doi:10.1002/ece3.2360 (2016).

28 Marques, A. *et al.* Increasing impacts of land use on biodiversity and carbon sequestration driven by population and economic growth. *Nat Ecol Evol* **3**, 628-637, doi:10.1038/s41559-019-0824-3 (2019).

29 Jayne, T. S., Snapp, S., Place, F. & Sitko, N. Sustainable agricultural intensification in an era of rural transformation in Africa. *Global Food Security* **20**, 105-113, doi:https://doi.org/10.1016/j.gfs.2019.01.008 (2019).

30 Mitchell, E. A. D. *et al.* A worldwide survey of neonicotinoids in honey. *Science* **358**, 109-111, doi:10.1126/science.aan3684 (2017).

31 Woodcock, B. A. *et al.* Impacts of neonicotinoid use on long-term population changes in wild bees in England. *Nat Comm* **7**, 12459, https://doi.org/10.1038/ncomms12459 (2016).

32 Rundlof, M. *et al.* Seed coating with a neonicotinoid insecticide negatively affects wild bees. *Nature* **521**, 77-80, (2015).

33 Schreinemachers, P. & Tipraqsa, P. Agricultural pesticides and land use intensification in high, middle and low income countries. *Food Policy* **37**, 616-626, https://doi.org/10.1016/j.foodpol.2012.06.003 (2012).

34 Network of African Science Academies (NASAC). Neonicotinoid Insecticides: Use and Effects in African Agriculture: a Review and Recommendations to Policymakers. (Available from: https://nasaconline.org/en/index.php/2020/05/26/neonicotinoid-insecticides-use-and-effects-in-african-agriculture-a-review-and-recommendations-to-policy-makers/, 2019).

35 Herrando, S. *et al.* Contrasting impacts of precipitation on Mediterranean birds and butterflies. *Sci Rep* **9**, 5680, doi:10.1038/s41598-019-42171-4 (2019).

36 Brookes, G. & Barfoot, P. (PG Economics Ltd, UK, https://pgeconomics.co.uk/pdf/globalimpactfinalreportJuly2020.pdf, 2020).

37 Farina, W. M., Balbuena, M. S., Herbert, L. T., Gonalons, C. M. & Vazquez, D. E. Effects of the Herbicide Glyphosate on Honey Bee Sensory and Cognitive Abilities: Individual Impairments with Implications for the Hive. *Insects* **10**, ARTN 354, doi:10.3390/insects10100354 (2019).

38 Zattara, E. E. & Aizen, M. A. Worldwide occurrence records suggest a global decline in bee species richness. *One Earth* **4**, 114-123, doi:https://doi.org/10.1016/j.oneear.2020.12.005 (2021).

39 Regan, E. C. *et al.* Global Trends in the Status of Bird and Mammal Pollinators. *Cons Let* **8**, 397-403, doi:10.1111/conl.12162 (2015).

40 Garibaldi, L. A. *et al.* Wild Pollinators Enhance Fruit Set of Crops Regardless of Honey Bee Abundance. *Science* **339**, 1608-1611, doi:10.1126/science.1230200 (2013).

41 Samnegård, U., Hambäck, P. A., Lemessa, D., Nemomissa, S. & Hylander, K. A heterogeneous landscape does not guarantee high crop pollination. *Proceedings. Biological sciences* **283**, 20161472, doi:10.1098/rspb.2016.1472 (2016).

42 Groeneveld, J. H., Tscharntke, T., Moser, G. & Clough, Y. Experimental evidence for stronger cacao yield limitation by pollination than by plant resources. *Perspect. Plant Ecol. Evol. Syst.* **12**, 183-191, doi:10.1016/j.appees.2010.02.005 (2010).

43 Lautenbach, S., Seppelt, R., Liebscher, J. & Dormann, C. F. Spatial and Temporal Trends of Global Pollination Benefit. *PLoS ONE* **7**, e35954 (2012).

44 Garibaldi, L. A., Aizen, M. A., Klein, A. M., Cunningham, S. A. & Harder, L. D. Global growth and stability of agricultural yield decrease with pollinator dependence. *Proceedings of the National Academy of Sciences* **108**, 5909-5914, doi:10.1073/pnas.1012431108 (2011).

45 Ritchie, H. & Roser, M. Urbanization. https://ourworldindata.org/urbanization (2018).

46 Hipolito, J., Boscolo, D. & Viana, B. F. Landscape and crop management strategies to conserve pollination services and increase yields in tropical coffee farms. *Agriculture Ecosystems & Environment* **256**, 218-225 (2018).

47 Begotti, R. A. & Peres, C. A. Rapidly escalating threats to the biodiversity and ethnocultural capital of Brazilian Indigenous Lands. *Land Use Policy* **96**, 10, doi:10.1016/j.landusepol.2020.104694 (2020).

48 Pirk, C. W. W., Strauss, U., Yusuf, A. A., Démares, F. & Human, H. Honeybee health in Africa—a review. *Apidologie* **47**, 276-300, doi:10.1007/s13592-015-0406-6 (2016).

49 Gebremedhn, H., Amssalu, B., Smet, L. D. & de Graaf, D. C. Factors restraining the population growth of *Varroa destructor* in Ethiopian honey bees (Apis mellifera simensis). *PLOS ONE* **14**, e0223236, doi:10.1371/journal.pone.0223236 (2019).

50 Junge, X., Lindemann-Matthies, P., Hunziker, M. & Schüpbach, B. Aesthetic preferences of non-farmers and farmers for different land-use types and proportions of ecological compensation areas in the Swiss lowlands. *Biol Cons* **144**, 1430-1440, https://doi.org/10.1016/j.biocon.2011.01.012 (2011).

51 Lee, H., Sumner, D. A. & Champetier, A. Pollination markets and the coupled futures of almonds and honey bees: simulating impacts of shifts in demands and costs. *American Journal of Agricultural Economics* **101**, 230-249, doi:10.1093/ajae/aay063 (2019).

52 Rucker, R. R., Thurman, W. N. & Burgett, M. Colony Collapse and the Consequences of Bee Disease: Market Adaptation to Environmental Change. *Journal of the Association of Environmental and Resource Economists* **6**, 927-960, doi:10.1086/704360 (2019).

53 Breeze, T. D. *et al.* Linking farmer and beekeeper preferences with ecological knowledge to improve crop pollination. *People and Nature* **1**, 562-572, doi:10.1002/pan3.10055 (2019).

54 Hall, D. M. & Martins, D. J. Human dimensions of insect pollinator conservation. *Current Opinion in Insect Science* **38**, 107-114, https://doi.org/10.1016/j.cois.2020.04.001 (2020).

55 Zommers, Z. *et al.* Burning embers: towards more transparent and robust climate-change risk assessments. *Nature Reviews Earth & Environment* **1**, 516-529, doi:10.1038/s43017-020-0088-0 (2020).

56 Duijm, N. J. Recommendations on the use and design of risk matrices. *Safety Science* **76**, 21-31, https://doi.org/10.1016/j.ssci.2015.02.014 (2015).

57 Peace, C. The risk matrix: uncertain results? *Policy and Practice in Health and Safety* **15**, 131-144, doi:10.1080/14773996.2017.1348571 (2017).

58 Morgan, M. G. Use (and abuse) of expert elicitation in support of decision making for public policy. *PNAS* **111**, 7176-7184, doi:10.1073/pnas.1319946111 (2014).

59 Regan, H. M., Colyvan, M. & Burgman, M. A. A taxonomy and treatment of uncertainty for ecology and conservation biology. *Ecological Applications* **12**, 618-628, https://doi.org/10.1890/1051-0761(2002)012[0618:ATATOU]2.0.CO;2 (2002).

60 FAO. FAOStat, http://www.fao.org/faostat/en/#data (2017).

61 Convention on Biological Diversity. Regional report for Africa on pollinators and pollination and food production. 1-49 (UNEP, UNEP/CBD/COP/13/INF/36, 2016).

62 Hill, R. *et al.* Biocultural approaches to pollinator conservation. *Nature Sustainability* **2**, 214-222, doi:10.1038/s41893-019-0244-z (2019).

63 Sutherland, W. J., Fleishman, E., Mascia, M. B., Pretty, J. & Rudd, M. A. Methods for collaboratively identifying research priorities and emerging issues in science and policy. *Methods Ecol Evol* **2**, 238-247, doi:10.1111/j.2041-210X.2010.00083.x (2011).

64 Wickham, H. (Springer-Verlag New York, https://ggplot2.tidyverse.org, 2016).

65 R Core Team. (R Foundation for Statistical Computing, Vienna, Austria https://www.R-project.org/, 2020).

66 Christensen, R. H. B. in *R package version 2018.8-25* (http://www.cran.r-project.org/package=ordinal/, 2018).

67 Menard, S. *Applied logistic regression analysis. Sage University Papers Series on Quantitative Applications in the Social Sciences* (SAGE Publications, Inc., 2002).

Acknowledgements

We thank the following people, who took part in an early scoping of this exercise during writing of the IPBES Pollination Assessment, helping to define the parameters: Aneni, T., Brosi, B., Cunningham, S., del Coro Arizmendi, M., Eardley, C., Espindola, A., Espirito Santo, M., Freitas, B., Gallai, N., Goka, K., Inouye, D., Jung, C., Kelbessa, E., Kwapong, P., Li, X., Lopes, A., Martins, D., Maus, C., Nates, G., Paxton, R., Pettis, J., Quezada-Euan, J., Settele, J., Szentgyorgyi, H., Taki, H., Veldtman, R., Wiantoro, S. We thank Sarah Barnsley and Lorna Blackmore, who supported the discussion groups as note-takers during the workshops. We are grateful to Tracey Balcombe and Caroline Vidler for planning and organising the workshop, and to Jiaxing Huang for support with the figures. We thank the University of Reading's Building Outstanding Impact Support Programme for supporting S.G.P., T.D.B. and D.S., and the workshop attendees. The authors would like to warmly thank IPBES for having dedicated its first assessment report to the important issue of pollinators and for having brought an unprecedented level of awareness on their importance and loss worldwide. This paper builds on some of the concepts from the IPBES pollination assessment and was, in many ways, inspired by that assessment. The views expressed here, however, represent the individual views of the authors. L.V.D is funded by the Natural Environment Research Council (Grant nos: NE/N014472/1 & 2).

Author contributions

L.V.D. conceived and designed the study. L.V.D and T.D.B. contributed equally to data collection, analysis and writing the paper. S.G.P. and H.T.N. convened the expert panel. S.G.P., D.S., T.D.B., H.T.N. and L.V.D. designed, organised and ran the workshop. L.V.D, T.D.B, H.T.N, A.J., M.A.A., P.B., D.B., L.G., L.A.G., B. Gemmill-Herren., B.G. Howlett, V.I-F., S.D.J, A.K-H., Y.J.K., H.M.G.L., T.L., C.L.S., A.J.V & S.G.P contributed to all rounds of scoring and discussion, commented on and edited the final manuscript. D.S. contributed to discussions, commented on and edited the final manuscript.

Competing interest declaration

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper. Correspondence and requests for materials should be addressed to Dr Lynn Dicks (lynn.dicks@zoo.cam.ac.uk). Reprints and permissions information is available at www.nature.com/reprints

Figure legends and captions

Figure 1 The four-box model for the qualitative communication of confidence, used by the IPBES[1].

Figure 2 Assessment of the importance of eight major drivers of pollinator decline[1], for six regions, and a global median (right). Importance is represented by circle size, reflecting median scores ranging from 1 ('not important) to 5 ('the most important') across 9-10 experts, following three rounds of anonymous scoring (Supplementary Table 2). Drivers are ordered according to effects on score values estimated by proportional odds models (see Supplementary Table 4), with higher scoring drivers at the top. All drivers except 'Pests and Pathogens' were scored significantly differently from 'Climate Change', either higher or lower. Degree of confidence is shown by the grey-scale, following the IPBES four-box model based on the confidence score and level of agreement, according to the criteria in Table 3. No driver was assigned a confidence category of 'Unresolved'. Background shading gradient from yellow to red indicates increasing importance of drivers as a cause of pollinator decline.

Figure 3 Assessment of the risks to human well-being associated with pollinator decline. Ten direct impacts are assessed separately, with risks evaluated based on probability, scale and severity of specific impacts occurring in six global regions. PD = Pollination Deficits, YI = Yield Instability, HP = Honey Production, FS = Food System Resilience, WF = Wild Fruit Availability, Pla = Wild Plant Diversity, Poll = Wild Pollinator Diversity, MP = Managed Pollinators, AV = Aesthetic Values, CV = Cultural Values. Scores are median scores across 5-10 experts, following three rounds of anonymous scoring (Supplementary Table 3). The underlying risk matrix, shown by the background colours, provides categories of risk according to an overall risk score (the product of probability, scale and severity scores): <10 = **low** risk; 10-27 = **moderate** risk; 28-50 **serious** risk; >50 = **high** risk. Degree of confidence is shown by the grey-scale, following the IPBES four-box model based on the confidence score and level of agreement, according to the criteria in Table 3. Impacts with the same scores on both axes are shown overlapping, jittered evenly, to enable confidence category to be visible.

Table 1 Direct drivers of pollinator decline defined by the IPBES[1] , including original wording shown in inverted commas, with section numbers indicated in brackets.

Short Form	**Definitions from IPBES pollination assessment[1]**
Pollinator management	Management, or husbandry, of bees (honey bees, bumblebees, stingless bees and solitary bees) for honey production, and of bees or other insects for pollination. "Two major *Apis* species are managed around the world: the western honey bee *Apis mellifera* and the eastern honey bee *Apis cerana*" (Section 2.4.2.1) "Five species of bumble bees are currently used for crop pollination, the major ones being *Bombus terrestris* from Europe and *Bombus impatiens* from North America." (Section 2.4.2.2). "Bee management is a global and complex driver of pollinator loss." (Section 2.4.3).
Pests and Pathogens	Parasites, pathogens and disease of all pollinating animals are included, both naturally circulating in populations and those associated with human management. "Bee diseases by definition have some negative impacts at the individual bee, colony or population level. Parasites and pathogens can be widespread in nature but may only become problematic when bees are domesticated and crowded." (Section 2.4.1)
Pesticide use	"Pesticides (fungicides, herbicides, insecticides, acaricides, etc.) are primarily used in crop and plant protection against a range of pests and diseases and include synthetic chemicals, biologicals, e.g., *Bacillus thuringiensis* (Bt) or other chemicals of biological origin such as spider venom peptides." (Section 2.3.1.) Veterinary medicines are also included.
Land management	"[…] Arrangements activities and inputs people undertake in a certain land cover type […]" (Section 2.2.1) This includes mowing, cultivating, grazing, burning and cropping regimes and non-pesticide inputs, particularly fertilizers. Pesticides were considered separately, as there are large amounts of evidence specific to them.
Land cover and configuration	"Land cover has been defined by the UN FAO as the observed (bio)physical cover on the earth's surface". (Section 2.2.1.) This includes the extent of different habitat and land use types, and their spatial configuration at landscape scale.
Invasive alien species	"Alien species are defined as a (non-native, non-indigenous, foreign, exotic) species, subspecies, or lower taxon occurring outside of its natural range (past or present) and dispersal potential (i.e. outside the range it occupies naturally or could occupy without direct or indirect introduction or care by humans) and includes any part, gametes or propagule of such species that might survive and subsequently reproduce. 'Alien invasive species' are alien species that become established in natural or semi-natural ecosystems, and are an agent of change, threatening native biological diversity" (Section 2.5.1)
GMOs	"Genetically modified (GM) organisms (GMOs) are organisms that have been modified in a way that does not occur naturally by mating and/or natural recombination. One of the most common methods to do this is by bioengineering transgene(s) into the new organism. The most common plant transgenes confer herbicide tolerance (HT), or toxicity towards herbivores (insect resistance, IR), although other characteristics have been also engineered (e.g., drought resistance in wheat, nutritional values in sorghum)." (Section 2.3.2.)
Climate change	"a change in the state of the climate that can be identified … by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer." (Section 2.6)

Table 2 Direct impacts of pollinator decline on human well-being defined by IPBES[1] , including original wording from Table 6.2.1[1] shown in inverted commas. For a definition of 'biocultural diversity' in this context, see Hill et al.[62]

Impact	Definition	Example
Impacts on food production		
Pollination Deficits	"Crop pollination deficit leading to lower quantity or visual/nutritional quality of food (and other products…)."	Reduction in the quantity or quality of food, fibre, fuel or seed that can be produced, as a result of pollinator loss.
Yield Instability	"Crop yield instability due to loss of pollinators or change in pollinator communities."	Crop yields becoming less stable or predictable between years, or locations.
Honey Production	"Fall in honey production (and other hive products)"	Reduction in the amount of honey or hive products that can be produced, as a result of pollinator loss
Food System Resilience	"Decline in long term resilience of food production systems"	Resilience is the ability of the food production system to withstand or recover from shocks or adverse effects, such as changes in climate.
Wild Fruit Availability	"Decline in yields of wild fruit, harvested from natural habitats by local communities"	Fruits or seeds harvested for food by people (not by animals). Could include, for example, blueberry harvesting from wetlands, or *Rubus fruticosus* fruits harvested from hedgerows.
Managed Pollinators	"Reduced availability of managed pollinators"	Managed pollinators are animals used to provide crop pollination, rather than for the production of honey.
Impacts on biocultural diversity		
Wild Pollinator Diversity	"Loss of wild pollinator diversity" leading to long term changes in network/food web interactions	Loss of species richness, or abundance of particular species of wild pollinators, including invertebrates and vertebrates. This impact is intermediate; ultimate impacts on human well-being can include food system resilience, aesthetic value, cultural practices and traditions.
Wild Plant Diversity	"Loss of wild plant diversity due to pollination deficit"	Loss of species richness, or abundance of particular species of wild plants due to pollination deficit. This impact is intermediate; ultimate impacts on human well-being can include loss of ecosystem services such as erosion prevention, aesthetic value, cultural practices and traditions.
Aesthetic Values	"Loss of aesthetic value, happiness or well-being associated with wild pollinators or wild plants dependent on pollinators"	This could include amenity values of specific plant communities, values of emblems or symbols, and the value of pollinators as sources of inspiration for art, music, literature, religion and technology.
Cultural Values	"Loss of distinctive ways of life, cultural practices and traditions in which pollinators or their products play an integral part"	Cultures, traditions and behaviours involving pollinators or pollinator products. This includes beekeeping, honey-hunting, specific dances or rituals associated with pollinators.

Table 3: Communication of the degree of confidence. We follow the four-box model for the qualitative communication of confidence (Figure 1). The degree of confidence in each finding is based on the quantity and quality of evidence, represented by confidence scores (see methods), and level of agreement among scorers, represented by inter-quartile ranges (IQRs) of expert scores for each variable.

Confidence category	**Definition**	**Thresholds, based on third round modified-Delphi scores**
Well established	Robust evidence High agreement	Confidence score ≥66.7% **AND** proportion unknowns<40% For risks, ∑IQRs ≤3; for drivers, IQR ≤1
Established but incomplete	Low quality evidence High agreement	Confidence score <66.7% **OR** ≥40% of responses “unknown” For risks, ∑IQRs ≤3; for drivers, IQR ≤1
Unresolved	Robust evidence Low agreement	Confidence score ≥66.7% **AND** proportion unknowns<40% For risks, ∑IQRs >3; for drivers, IQR >1
Inconclusive	Low quality evidence Low agreement	Confidence score <66.7% **OR** ≥40% of responses “unknown” For risks, ∑IQRs >3; for drivers, IQR >1

Methods

We assessed drivers and risks using a modified version of a formal consensus method known as the Delphi technique[24], in which the second and third rounds of anonymous, independent scoring took place following detailed discussions at a face-to-face workshop in November 2017. This modification of the Delphi technique is frequently used in environmental research, where issues are multi-disciplinary and interpretations of the same phrase can differ strongly among individuals[63]. All but one of the authors of this paper (hereafter 'experts') took part in all rounds of the Delphi process (D.S. facilitated only and did not score). This set of 20 pollination experts was carefully selected to cover the range of necessary expertise, including biodiversity science, economics, social science and indigenous and local knowledge, and to ensure that the main global regions were each represented by at least two scorers either originating from or mainly working in that region. Thirteen of the 21 authors (62%) were also authors of the IPBES global pollination assessment[1], mostly nominated by their respective national governments, and the team had a balanced gender ratio of 11 men : 10 women.

Definitions of regions, parameters and scores

We divided the world into six global regions, largely representing geographic continents of North America, Latin America, Asia, Europe, Africa and Oceania, with two key differences: i) we included the Pacific islands in a region known as 'Asia-Pacific', rather than combining them with Australia and New Zealand in the geographic continent 'Oceania'. Our 'Asia-Pacific' region is equivalent to most of the Asia-Pacific as defined by IPBES, but excludes Australia and New Zealand. We named 'Australia/New Zealand' as a separate region, because they are very different from mainland Asia and the Pacific islands, both biogeographically and geopolitically (see Figure S1); ii) we included the countries of Central America and the Caribbean with Latin America, rather than with North America as they would be in the geographic continent. Our ‘Latin America’ region includes the subregions of Mesoamerica, the Caribbean and South America, as defined by IPBES (see Figure S1).

For each region, experts individually assigned probability, scale and severity scores for each of ten impacts of pollinator decline, and importance scores to each of eight drivers of pollinator declines defined by the IPBES[1] (Table 1), using the five-point Likert scales described in Supplementary Table 1. All scores were accompanied by a *confidence* score of low, medium or high, enabling experts to qualify their judgements with a level of confidence, based on the amount of evidence they were aware of, and its quality.

The following definitions of probability, scale and severity were available for authors to consult throughout the process:

Probability: A high probability of impact suggests that the impact is already taking place or is very likely, at least in some circumstances. Low probability implies that the impact is *not* taking place or is unlikely. Unknown means there is not enough evidence to make a judgement on whether or not the impact is happening or likely to happen.

Scale of impact either refers to the numbers of people or area affected. Large means there is evidence for impacts on people and livelihoods, either over a large area or affecting many people. Moderate means there is evidence for impacts on people and livelihoods, either over a moderate area or affecting a moderate proportion of people, and small means there is evidence for impacts on people and livelihoods, either in a small, localised area, or only affecting a small number of people. Unknown means there is not enough evidence on the scale of this impact to make a judgement.

Severity of impact refers to the nature of the impact on individual people or families. Large means there is evidence for a substantial or severe impact on people and livelihoods. Moderate means there is evidence for a moderate impact on people and livelihoods, and small means a small impact. Unknown means there is not enough evidence on the severity of this impact to make a judgement.

Experts rated the *importance* of each driver in affecting pollinators, at the present time, in each specific region, on a 1-5 scale from ‘not important’ to ‘the most important’ (Table 1 and Supplementary Table 1).

We set an *a priori* expectation of consensus as an interquartile distance of < 2 between scores for a particular element (not including confidence). This still allowed us to distinguish between high and low agreement following criteria in Table 3, in which high agreement is denoted by mean IQR ≤1 (where half of all scores are the same or an adjacent score) (Table 3).

Three iterative rounds of scoring

In an initial scoping phase, all experts were invited to comment on the proposed scoring structure described above. Following this, the first round of scoring was conducted online in October 2017. Each expert was asked to score for all regions, considering the evidence in the IPBES report[1] alongside their own expertise. Experts could add comments to support their scores, and were encouraged to cite parts of the IPBES report[1] and other specific literature. Scores and comments were compiled, anonymously, and summaries sent to all experts, detailing the median and interquartile range of scores for each element, and the proportions of ‘unknown’ responses.

Each expert was then assigned a region (always one they were familiar with) and a driver, and asked to play a cynic role, doing focused background research to challenge, refute or support the scores from the first round, with evidence. Cynic roles were not made known during later discussions, but cynics were invited to comment appropriately and to actively introduce new evidence to the discussions.

In November 2017, all experts attended a three-day, face-to-face workshop in Reading, UK. Experts were divided into two groups, which each discussed the results from the first round, and the evidence that supports them, for three regions. Group 1 discussed and scored in rounds 2 and 3 for Europe, North America and Africa; Group 2 discussed and scored Latin America, Asia Pacific and Australia/New Zealand. Discussions were facilitated and notes taken throughout. Facilitators kept in contact and discussed any specific issues arising about how to score, to ensure that both groups responded in the same way. At the end of each part of the discussion, participants scored again for each element of risk, and each driver, for each region in turn. Scoring was conducted independently and anonymously, using Excel spreadsheets on personal laptops. All members of a group were encouraged to score for each region discussed in their group, with the following guidance: "Score if you can (but you don't have to). If you feel confident to score for a region outside your own personal knowledge, please do so. These issues are complex and open to interpretation. This is why we employ a subjective scoring process, with anonymous scoring. Listen to the discussion, and then score as you understand it."

These round 2 results were compiled as before, and any scores with interquartile range (IQR) ≥2 (our *a priori* criterion for consensus), progressed to round 3 for rescoring.

Round 3 scoring took placed on the third day of the workshop in a plenary discussion. This allowed a further opportunity for any consistent differences in scoring or approach across groups to be revealed, but none were evident. Second round scores were presented and made the subject of debate and discussion. Experts scored again anonymously and independently, using laptops, for the regions they scored for in round 2, although the discussion was open to both groups. In total, 19 variables (3 drivers, 16 impacts) were rescored, along with associated confidence levels. Due to an error, four impact variables (Latin America: Pollination Deficit [severity], Yield Instability [scale], Wild Fruit Availability [scale], Wild Plant Diversity [scale]) with IQR ≥2 were not flagged for rescoring during the workshop and were later rescored during a teleconference. Only five of the ten scorers from group 2 were able to attend the teleconference, due to time differences, so these four variables have only n=5 scorers in the final dataset (Figure S3). All other variables have at least 8 scorers. Following the third round, three variables still failed to reach consensus (IQDs ≥2) - Australia/New Zealand: Pollination Deficit [probability], Wild Fruit Availability [probability] and Latin America: Managed Pollinators [probability] (Figure S3).

Analysis Median scores following the third round of scoring were used to derive risk scores (the product of probability, scale and severity scores) and associated risk categories (boundaries visualised in Figure 3), importance scores for drivers, and confidence categories for all final scores, following criteria given in Table 3. In assigning confidence categories, the quantity and quality of evidence was based on assigned confidence scores for each risk or driver. The confidence score is the percentage of the maximum possible confidence score (9 for risks, 3 for drivers), represented by the median confidence scores from the final round, with the three medians summed in the case of impacts (confidence score for risk = (∑ Confidence scores for probability, scale and severity/9) * 100)).

Overall global scores for the importance of drivers were calculated as a median of the six region-level scores and confidence scores, to ensure equal weight was given to each region (although the numbers were unchanged if individual scores across all six regions were used). We did not calculate overall global risk scores for different impacts of pollinator decline, because these scores were based on assessments of probability, scale and severity for different global regions and it does not make sense to average these across regions. All figures were drawn using the ggplot2 package[64], in R version 4.0.0[65].

We hypothesized that the scores participants gave for each component of the risk, or driver importance, were dependent on the impact, or driver, being scored, and on the region being scored, rather than reflecting individual scorer differences. We tested this hypothesis using Cumulative Link Models and Cumulative Link Mixed Models with logit link functions (also called proportional odds or ordinal logistic regression models), with the ordinal package[66], in R version 4.0.3[65]. The top and bottom two score categories (scores 1 and 2, and 4 and 5 respectively) were collapsed to create three-point scales for probability, scale and severity of impacts, and importance of drivers.

We considered the effect of Region and Impact, or Region and Driver, on score, for each of four dependent variables: probability, scale, severity and importance. ‘Unknown’ responses were treated as ‘na’ for this analysis. The dataset was not large enough to examine the interaction between Region and Impact or Driver with this type of model ($n \leq 10$ scorers for each combination of factors).

For each model, we tested the proportional odds assumption, that the effects of region or impact group were the same, regardless of where the cut-off points were placed across the three score categories, using the nominal test and scale test functions, which use likelihood ratio tests. When this assumption was violated, we used partial proportion odds models where possible, given our data structure. Independent variables that failed the tests were examined, with scale (dispersion of latent variable) allowed to vary among levels of the dependent variable (failure of the scale test) or effects of the relevant factor assumed to be nominal rather than ordinal (failure of the nominal test).

These models do not account for the random effects of scorer or group, because the scorers were divided among two separate groups, each of which only scored half of the regions. We ran Cumulative Link Mixed Models separately for each group, including scorer as a random effect to account for differences between individual scorers. The effects of group cannot be analysed as a random factor with this study design, because there are only two levels. The effect of Group cannot be separated from the effect of Region in a single model.

We used McFadden's pseudo R^2 value (ρ^2) to provide an indication of goodness of fit for all models, as recommended by Menard (2002)[67]. This is calculated relative to a null model using the following equation:

$$\rho^2 = 1 - \frac{LL_{mod}}{LL_0}$$

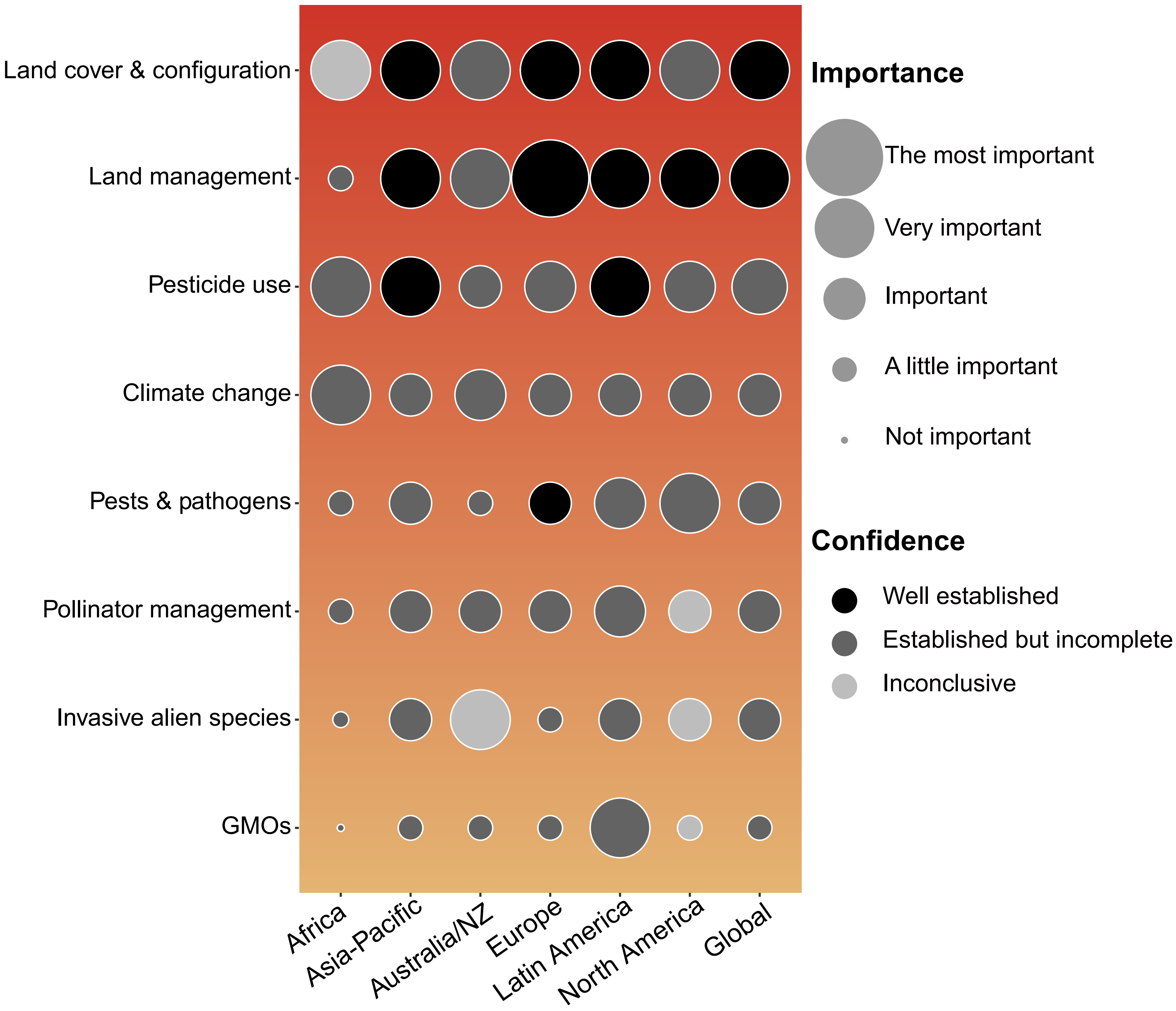
where LL_{mod} is the log likelihood value for the fitted model and LL_0 is the log likelihood for the null model which includes only an intercept as predictor (so that every score is predicted the same probability).

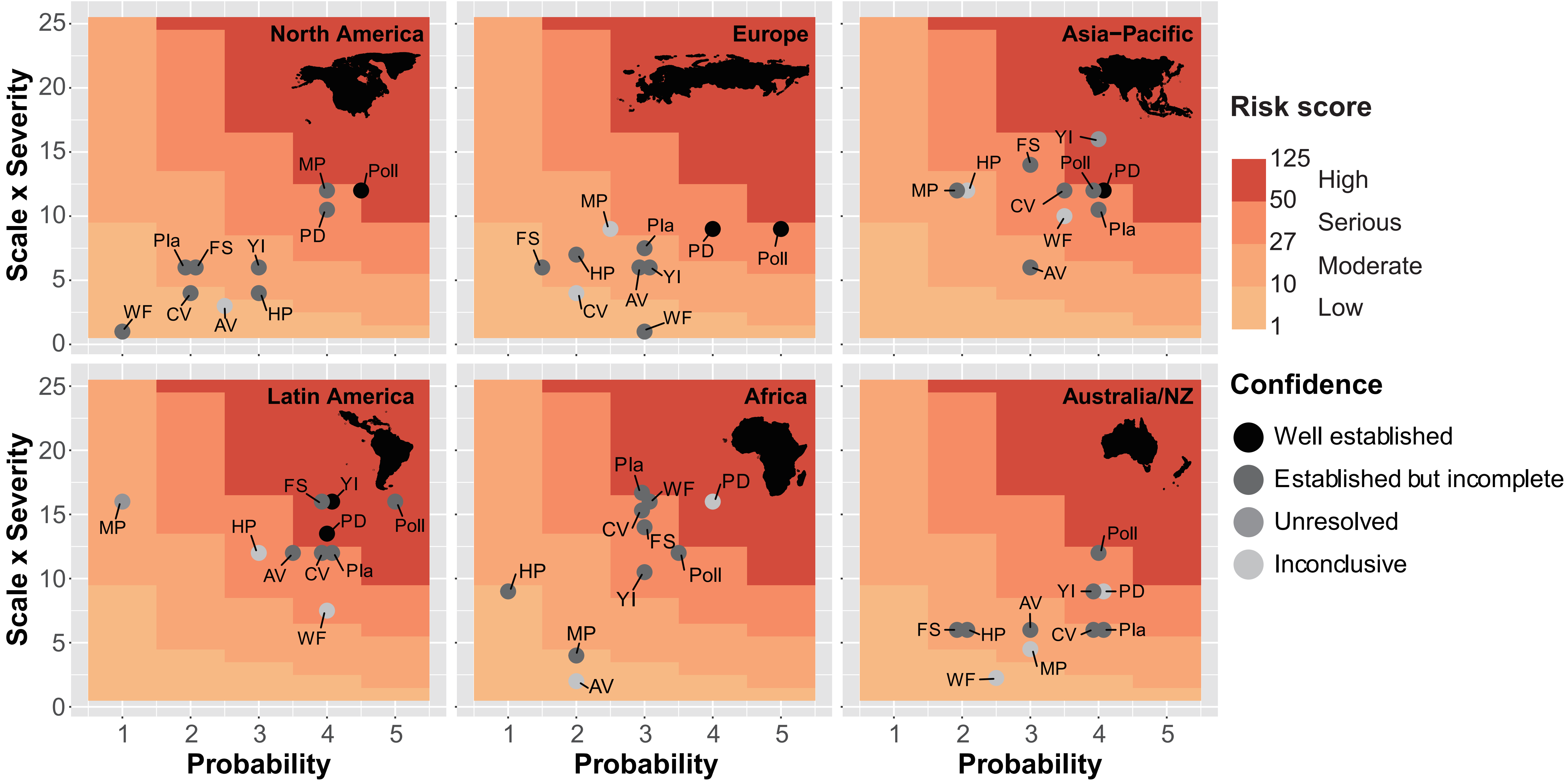
Results of this analysis are provided and discussed in the Supplementary Information (Supplementary Tables 4-9 and accompanying text).

Data availability statement

Figures 2 and 3 represent scores from round 3 of a Delphi process with n=20 expert scorers. Medians and Interquartile ranges for these scores are presented in full in the Supplementary Information (Supplementary Tables 2 and 3); the raw data are shown in Extended Data Figures 2 and 3.


High
LEVEL OF AGREEMENT
Established
but incomplete
Well established
Inconclusive
Unresolved
Low
Robust
QUANTITY AND QUALITY OF EVIDENCE
High
CERTAINTY SCALE
Low


Land cover & configuration
Land management
Pesticide use
Climate change
Pests & pathogens
Pollinator management
Invasive alien species
GMOs
Africa
Asia-Pacific
Australia/NZ
Europe
Latin America
North America
Global
Importance
The most important
Very important
Important
A little important
Not important
Confidence
Well established
Established but incomplete
Inconclusive


North America
Europe
Asia−Pacific
Latin America
Africa
Australia/NZ
Scale x Severity
Probability
0
5
10
15
20
25
1
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MP
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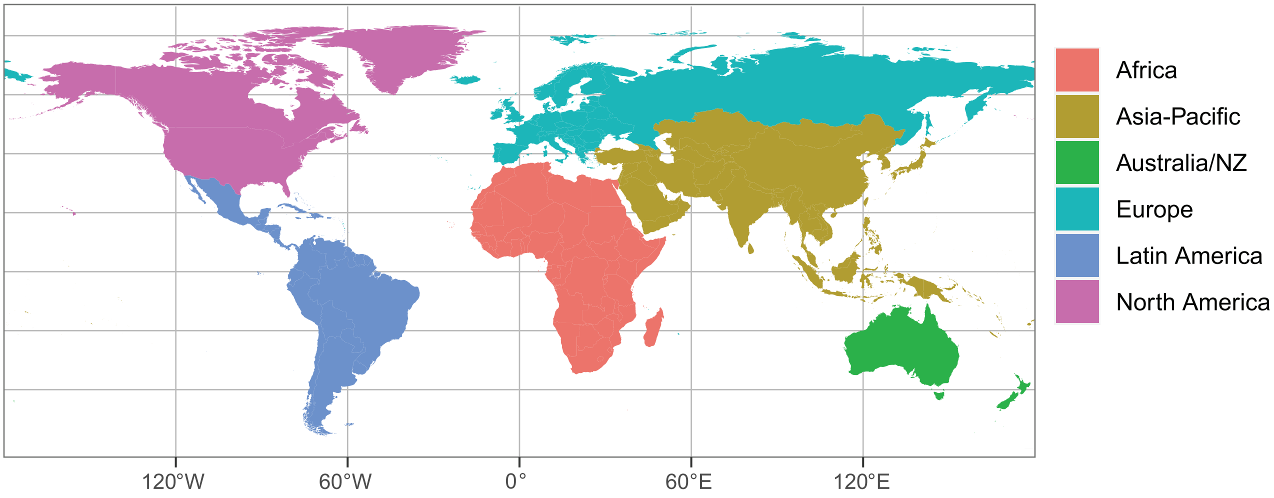
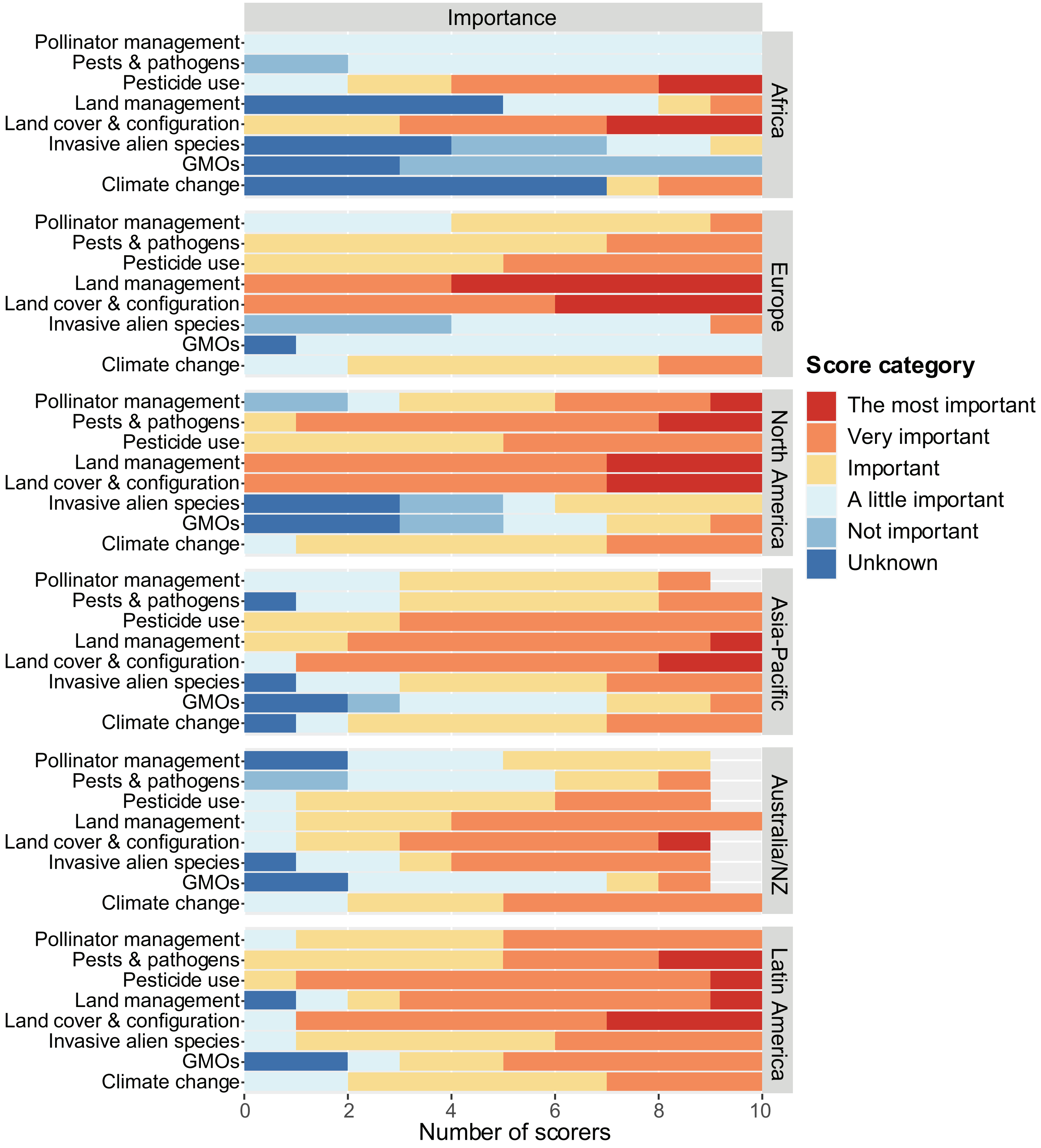
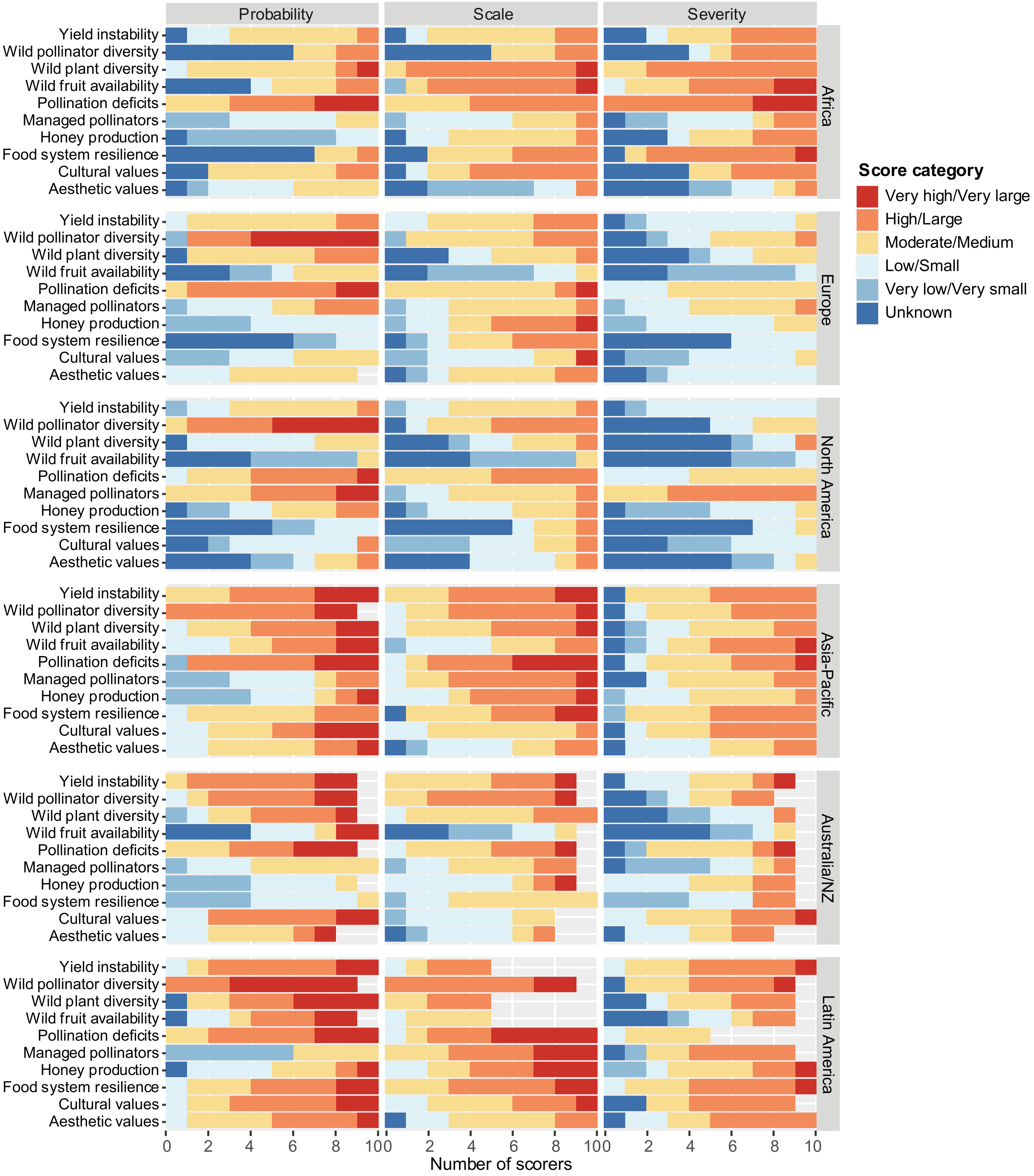
PD
Pla
FS
YI
WF
CV
AV
HP
Risk score
125
50
27
10
1
High
Serious
Moderate
Low
Confidence
Well established
Established but incomplete
Unresolved
Inconclusive


120°W
60°W
0°
60°E
120°E
Africa
Asia-Pacific
Australia/NZ
Europe
Latin America
North America


Importance
Africa
Europe
North America
Asia-Pacific
Australia/NZ
Latin America
Pollinator management
Pests & pathogens
Pesticide use
Land management
Land cover & configuration
Invasive alien species
GMOs
Climate change
0
2
4
6
8
10
Number of scorers
Score category
The most important
Very important
Important
A little important
Not important
Unknown


Probability
Scale
Severity
Yield instability
Wild pollinator diversity
Wild plant diversity
Wild fruit availability
Pollination deficits
Managed pollinators
Honey production
Food system resilience
Cultural values
Aesthetic values
Africa
Europe
North America
Asia-Pacific
Australia/NZ
Latin America
0
2
4
6
8
10
Number of scorers
Score category
Very high/Very large
High/Large
Moderate/Medium
Low/Small
Very low/Very small
Unknown