Assessing Transparency and Reproducibility in Invasion Science

Fabio Mologni[1, 2]

*Jason Pither[1]

* Co-corresponding authors

*1. Department of Biology, and Institute for Biodiversity, Resilience, and Ecosystem Services

I.K. Barber Faculty of Science, University of British Columbia Okanagan

3187 University Way, Kelowna, BC V1V 1V7, Canada

Email: jason.pither@ubc.ca

ORCiD: https://orcid.org/0000-0002-7490-6839

2. Department of Botany and Biodiversity Research

University of Vienna, Rennweg 14, 1030, Vienna, Austria

Phone: +43 670 1812022

ORCiD: https://orcid.org/0000-0003-4750-9974

Abstract

Policymakers and practitioners overseeing invasive species management depend on reliable research for guidance. Transparency and reproducibility are core features of reliable research, and prerequisites for successful study replication, but are evidently lacking in many science disciplines. Whether this shortfall characterizes invasion science remains unknown. We evaluated a sample of invasion science studies for their adherence to practices that enhance transparency and reproducibility, such as making data and code available, and explicitly considering statistical power. Our evaluation focused on published studies concerning two plant species invasive to riparian ecosystems in British Columbia, Canada (*Elaeagnus angustifolia* and *Phalaris arundinacea*), as these contributed to a broader systematic mapping initiative. Our systematic literature search yielded 746 studies, of which 45 met our predefined inclusion criteria (relevance rate = 6%). We assessed each study against a 14-item checklist (motivated by the Transparency and Openness Promotions guidelines) and a corresponding scoring rubric. On average, studies achieved a score of 26%, with no studies addressing statistical power, pre-registering their plans, and few making data or code publicly available. There is a clear need and opportunity for improving the transparency and reproducibility of invasion science research. We refer researchers to resources aimed at improving research practices, and discuss two practices that are especially important in the context of applied invasion science: power analysis and sharing data and code. We echo recent calls for educational and research institutions to expand access to training in open science, and urge policymakers and practitioners to consider transparency and reproducibility when seeking guidance from invasion science research.

Keywords: Invasion science, Reproducibility, Open Science, Non-native species, Invasive species, Impacts, Riparian ecosystems, Foreshore ecosystems, British Columbia, Reed Canarygrass, Russian Olive

Introduction

Globally, biological invasions are estimated to cost over 423 billion USD each year, a number that has quadrupled every decade since 1970 (Roy et al., 2024). Ideally, policymakers and managers tasked with addressing the threats and impacts of invasive species base their decisions and actions on reliable research, thus maximizing potential success, and minimizing waste in time, effort, and money. “Reliable” means that the research adheres to foundational principles of scientific inquiry, i.e. it is reproducible (definition in Box 1), and that independent efforts to replicate the findings would be successful. Worryingly, evidence suggests that a sizeable fraction of published research, across a variety of disciplines including ecology (Kelly, 2019), is irreproducible (Baker, 2016), and replication efforts in fields such as psychology (Open Science Collaboration, 2015) and medicine (Begley & Ioannidis, 2015) have met with limited success.

A variety of shortfalls can render scientific research irreproducible (Parker, Forstmeier, et al., 2016), including failing to fully and transparently report all procedures (e.g. details of sampling and/or experimental design and statistical analyses, Davis & Kay, 2023; Parker et al., 2016), and failing to make code and data available and useable (Culina et al., 2020; Popovic, Mason, Drobniak, Marques, Potts, Joo, Altwegg, Burns, McCarthy, Johnston, Nakagawa, McMillan, Devarajan, Taggart, Wunderlich, Mair, Martínez-Lanfranco, et al., 2024; Riordan-Short et al., 2023; Roche et al., 2015a). Addressing such shortfalls does not, however, guarantee that findings will be replicated. For example, a study may be reproducible thanks to thorough and transparent reporting, but if it suffers from low statistical power its findings are less likely to be replicated (Button et al., 2013; Yang et al., 2023). It is recommended that studies achieve a power of at least 80% (Button et al., 2013), but a recent estimate of the average power in primary ecology and evolutionary biology studies was 15% (Yang et al., 2023), slightly lower than other disciplines (e.g. 20% in medical sciences, Lamberink et al., 2018).

Low statistical power in invasion science can reduce the likelihood of detecting impacts of invasive species. Previous work evaluated 31 analyses testing for the ecological impacts of nonnative species, finding that 97% (n=30) had insufficient power to detect if the reported impact (or lack thereof) existed (or not, Davidson & Hewitt, 2014). Less well-known consequences of low statistical power, and previously overlooked (Davidson & Hewitt, 2014), are increases in the rate of false positives (Type-I errors), errors in effect magnitudes (Type M) and errors in effect signs (Type S, (Button et al., 2013; Parker et al., 2018; Parker & Yang, 2023). When combined with the potential influences of P-hacking and HARKing (i.e. hypothesizing after the results are known, Munafò et al., 2017), it is conceivable that a substantial proportion of published studies in invasion science present findings that exaggerate impacts or even misrepresent the true direction of effects.

Here we report the results of an evaluation of invasion science research with respect to its adherence to practices that enhance transparency and reproducibility. We were motivated to undertake this assessment while conducting a separate project focused on producing a systematic map of the evidence on the impacts of a selection of plant species invasive to riparian ecosystems in British Columbia (Mologni et al., 2023a). While compiling the studies, we found substantial variation in reporting practices, including among studies on the same species. We therefore decided to more formally evaluate a subset of the publications with reference to a checklist of practices that are recommended to maximize transparency and reproducibility.

Methods

Our assessment focused on studies concerning two plant species invasive to riparian ecosystems in British Columbia, Canada: *Elaeagnus angustifolia* (Russian Olive) and *Phalaris arundinacea* (Reed Canarygrass, thereafter RO and RCG respectively). We systematically identified all studies investigating their impacts on riparian ecosystems within North America (excluding Mexico), following the ROSES reporting standards for systematic maps and reviews (Haddaway et al., 2018). A detailed description can be found in the protocol of our systematic map (Mologni et al., 2023a, 2023b). For the present study, we applied an additional filter: we removed studies published before the year 2000. This reflects a balance between excluding years in which there was limited awareness around reproducibility in ecology, with the need for a sufficient time period over which to reveal any obvious trends in reporting practices. We assume that the literature we reviewed is representative of invasion science research in general.

To appraise the level of adherence to practices that enhance transparency and reproducibility, we assessed each article against a checklist and corresponding scoring rubric. Our checklist is a streamlined version of a checklist developed previously in our lab (Kast et al., 2023 see Appendix 1), which aimed to balance the operational simplicity of the "transparency and openness promotion" guidelines developed by the Center for Open Science (https://www.cos.io/initiatives/top-guidelines) with the more demanding evaluation steps of the checklist for peer reviewers developed by (Parker et al., 2018). It was also informed by the "transparency checklist" of Aczel et al. (2020).

The checklist includes 14 items, and to each we assigned a score of "0" if not addressed, "1" if partially addressed, "2" if addressed or "n/a" if not applicable. We calculated the final study score by summing the item scores and dividing by the number of applicable questions. All items are equally weighted. The final score was halved and multiplied by 100 to convert it to a percentage.

The items fall into four categories and include the following questions:

- Pre-registration (see Discussion): was the study pre-registered and were deviations from planned methods described?

- Materials availability: were availability statements included? Were data and code stored in openly accessible repositories and links and licences provided? Was the description of the experimental protocol sufficiently comprehensive to allow for replication?
- Study design: was sample size determined (e.g. with a priori power analysis) and randomization described? If applicable, as the study authorized (i.e. a relevant permit was obtained if required)?
- Data analysis: were statistical methods justified and associated assumptions checked?

The full list and description of items can be found in the supplementary material (Appendix 1).

We calculated the overall, by-year and by-item average scores. We identified areas of weakness and strength using average scores by item. We arbitrarily categorized scores below 20% as "*overlooked*", between 20 and 80% as "*in progress*" and above 80% as "*addressed*".

We did not complete a pre-registration for this study because it does not include any formal statistical analyses or inferences, and we initiated this study after some of the literature search and evaluation activities had already been completed as part of a concurrent literature review (Mologni et al., 2023a).

Results

Our systematic literature search yielded a total of 746 studies, 335 for RO and 411 for CRG (Figure 1). The majority were extracted from Web of Science (n = 405), followed CABI Invasive Species Compendium (n = 175). Two reviews were identified for RO and one for CRG. Katz & Shafroth (2003) focused on RO and all references were screened (n=162). Lalk et al. (2021) investigated the impacts of several woody species and we selected only studies referring to RO (n=6). Zedler & Kercher (2004) focused on wetlands and only references regarding CRG were extracted (n = 7). After removing studies published before the year 2000, we obtained 46 studies. One appeared in both searches and was thus excluded. The final list contained 45 studies, with an overall relevance rate (i.e. the percentage of studies included after screening and removing duplicates, Ridley et al., 2022) of 6%.

The average score across all 45 studies was 26% and ranged from 11 to 50%. The number of publications and scores increased slightly over time (Figure 2). Ten items averaged a score below 20% and were categorized as "*overlooked*" (Figure 3). Four items scored 0 across all studies: pre-registration, code link, code licence and sample size determination. The other 6 items averaged between 0 and 20%: the material availability statement (score = 5%), data availability statement (16%), data link (7%), data licence (2%), code availability statement (3%), and study authorization (19%, Figure 3). Two items were between 20% and 80%: randomization (40%) and assumptions (71%) and were categorized as "*in progress*" (Figure 3). Two items were above 80% and were experimental protocol (96%) and statistics (89%), and marked as "*addressed*" (Figure 3).

Discussion

The cost of managing biological invasions has quadrupled every decade since the 1970s, with no signs of slowing down (Roy et al., 2024). To optimize the allocation of limited financial and personnel resources, the research informing managers and policy-makers must be transparent, reproducible, and ideally replicable. Our findings clearly show that there is much room for improvement. On average, only a quarter of the reproducibility criteria were satisfactorily addressed across 45 studies in invasion science. The majority were addressed only sporadically. This is consistent with previous findings in psychology (Open Science Collaboration, 2015), medicine (Begley & Ioannidis, 2015), and ecology (Parker, Forstmeier, et al., 2016; Roche et al., 2015a).

Two items were categorized as "*addressed*": describing experimental design and statistics. The importance of reporting detailed experimental designs and statistical analyses has long been recognized and thus generally implemented in scientific research. We did not evaluate the appropriateness of the experimental design and statistical analyses, as this was beyond the scope of our study. Two items were categorized as "*in progress*": on average, more than two-thirds of the studies sufficiently described and justified meeting assumptions of statistical tests. More than a third stated if randomization occurred and described why or why not.

Most items (10 out of 14) scored below 20% and were deemed as "*overlooked".* Material availability statements were rarely provided, highlighting the inability to recover original specimens and samples. This includes, for example, no mention of the existence of voucher specimens when these are relevant. Surprisingly, less than a third of the studies provided a data availability statement. Of these, the majority (n=9) provided data as supplementary information and only three a proper data availability statement, two linked to a repository (Price et al., 2018; Rowe et al., 2019). Price et al. (2018) was the only study that provided a data licence too. These findings align with a previous review of data availability statements (Federer et al., 2018) and contrast with current journal policies, which generally require data availability statements and encourage storing and sharing data in a repository. Code availability statements were largely absent too, despite code availability being identified as one of the principal barriers to reproducibility in science (Kambouris et al., 2024). Two studies included a code availability statement, but only one provided access to code; however, shared as supplementary information. No study provided a link and licence to code.

No study conducted power analyses to pre-determine the sample size. Low statistical power increases the chances of missing (Type II error, (Davidson & Hewitt, 2014) and overestimating impacts (Type M error, Parker & Yang, 2023; Yang et al., 2022). Similarly, no study completed a pre-registration. Pre-registration reduces bias and encourages thorough preplanning (Yang et al., 2023), including power analyses. Low average scores were also identified for study authorization.

Open science policies of the main journals in invasion science vary considerably (i.e. Biological Invasions, Neobiota, Invasive Plant Science and Management, and Wetlands, the latter being the most common journal in our bibliographic sample). These journals consistently encourage data sharing, sometimes in specialized repositories; however, this is not mandatory. Biological Invasions is the only journal that requires a data availability statement, albeit this does not require data themselves to be made available. Invasive Plant Science and Management encourages best practices in reporting methodologies, while Neobiota strongly encourages depositing methods and "protocols" in a repository (we consider a protocol akin to a pre-registration). Yet again, these policies are not mandatory. On the other hand, Springer journals (Biological Invasions and Wetlands) require sharing voucher specimens and identifiers. Wetlands also requires the submission of specific data and materials (i.e. proteins, DNA, and RNA sequences) to appropriate repositories. All in all, policies vary greatly across journals, are typically non-mandatory and cover only a fraction of open science good practices.

Other journals in ecology are adopting stronger open science policies. For instance, some journals allow for the automatic publication of studies as preprints or allow direct transfer from preprint repositories upon submission (Proceedings of the Royal Society B). Other journals have partnerships with data repositories (Journal of Biogeography) or require publicly accessible archiving of the data (Ecology). In the last few years, data availability statements have increasingly become mandatory, and many journals now require authors to share their code too (Proceedings of the Royal Society B), to the point that the American Naturalist now enlists data editors to evaluate data and code sharing of each manuscript submitted to the journal. Finally, Environmental Evidence requires registering a protocol (i.e. preregistration) in an open-access repository. Still, consistency in journal policies concerning open science good practices is lacking.

We encourage invasion science researchers to consult the commentary by O'Dea et al. (2021), who provide a thoughtful assessment of the ways researchers, publishers, and funders can facilitate progress towards more open, transparent, and reliable research, and also underscore the importance of adjusting incentives and removing barriers for researchers (Baker, 2016; Strømme et al., 2022). We also highlight the contributions of Filazzola and Cahill (2021) and (Cooke et al., 2017), the former providing insightful discussion about study design and different forms of "replication" in ecology, and the latter presenting cogent advice on experimental design for informing conservation ecology - which has clear parallels to invasion science. Below we highlight (i) addressing statistical power and (ii) sharing code and data as key steps within the context of invasion science research, which often seeks to inform management policy and allocation of resources.

An adequate statistical power (e.g. a goal of 80% power) reduces the chances of missing and overestimating impacts. Although individual research groups often lack funding and resources to achieve adequate statistical power, it is nevertheless worthwhile to undertake a prospective power analysis and clearly report its outcomes. If the desired power can be achieved, then communicating this will strengthen confidence in the study outcomes. Acknowledging that a study falls short of the desired power is equally important and beneficial, and this acknowledgment can readily be included in the standard "study limitations" section of the Discussion. More generally, we suggest a section on statistical power should be routine in every invasion science study, and ideally communicate what implications the achieved power (be it lower than desired or not) may have for their study. Doing so will help raise awareness among scientists and practitioners about the critical importance of statistical power, and how, for example, it influences the risk of missing, overestimating, or underestimating impacts (Davidson & Hewitt, 2014; Parker & Yang, 2023). It is noteworthy that as early as the 1990s the Journal of Wildlife Management required authors to address statistical power, recognizing its importance to management-related research.

Given that individual ecological studies rarely achieve the desired statistical power (Davidson & Hewitt, 2014; Yang et al., 2022), it is especially important for researchers to make their data openly available and useable (when ethically reasonable to do so), such that they can contribute to meta-analyses. When the desired power cannot be achieved due to resource constraints (as is commonplace), coordinated distributed experiments offer a solution by combining the efforts of multiple teams (Filazzola & Cahill Jr, 2021; Fraser et al., 2013; Yahdjian et al., 2021). Such collaborative approaches are becoming increasingly common in invasion science and ecology in general (e.g. Knollová et al., 2024; van Kleunen et al., 2019) and should be prioritized by funding agencies (Packer et al., 2017).

Invasive species managers and policymakers rely on research outputs to inform their decisions and actions. Our findings highlight an opportunity and need to improve the transparency, openness, and reproducibility of invasion science research. Ultimately, addressing this challenge in invasion science will help ensure resources are allocated optimally, and in ways that maximize success. For researchers, checklists (e.g. Aczel et al., 2020; Parker et al., 2016), recent guidelines (Popovic, Mason, Drobniak, Marques, Potts, Joo, Altwegg, Burns, McCarthy, Johnston, Nakagawa, McMillan, Devarajan, Taggart, Wunderlich, Mair, Martínez-Lanfranco, et al., 2024), and example workflows (e.g. Pither, 2024) can facilitate progress toward better practices, and the Society for Open, Reliable, and Transparent Ecology and Evolutionary Ecology (SORTEE) provides a list of helpful resources (https://www.sortee.org/other_resources/). We highlight Roche et al. (2015) and (Abdill et al., 2024) for advice on sharing data and code, respectively. Lastly, we emphasize that adapting research protocols towards the ideal takes time, and researchers should embrace and celebrate every advance made, however small.

References

Abdill, R. J., Talarico, E., & Grieneisen, L. (2024). A how-to guide for code sharing in biology. *PLOS Biology*, *22*(9), e3002815. https://doi.org/10.1371/journal.pbio.3002815

Aczel, B., Szaszi, B., Sarafoglou, A., Kekecs, Z., Kucharský, Š., Benjamin, D., Chambers, C. D., Fisher, A., Gelman, A., Gernsbacher, M. A., Ioannidis, J. P., Johnson, E., Jonas, K., Kousta, S., Lilienfeld, S. O., Lindsay, D. S., Morey, C. C., Munafò, M., Newell, B. R., … Wagenmakers, E.-J. (2020). A consensus-based transparency checklist. *Nature Human Behaviour*, *4*(1), Article 1. https://doi.org/10.1038/s41562-019-0772-6

Baker, M. (2016). 1,500 scientists lift the lid on reproducibility. *Nature*, *533*(7604), Article 7604. https://doi.org/10.1038/533452a

Begley, C. G., & Ioannidis, J. P. A. (2015). Reproducibility in Science. *Circulation Research*, *116*(1), 116–126. https://doi.org/10.1161/CIRCRESAHA.114.303819

Button, K. S., Ioannidis, J. P. A., Mokrysz, C., Nosek, B. A., Flint, J., Robinson, E. S. J., & Munafò, M. R. (2013). Power failure: Why small sample size undermines the reliability of neuroscience. *Nature Reviews Neuroscience*, *14*(5), 365–376. https://doi.org/10.1038/nrn3475

Cooke, S. J., Birnie-Gauvin, K., Lennox, R. J., Taylor, J. J., Rytwinski, T., Rummer, J. L., Franklin, C. E., Bennett, J. R., & Haddaway, N. R. (2017). How experimental biology and ecology can support evidence-based decision-making in conservation: Avoiding pitfalls and enabling application. *Conservation Physiology*, *5*(1), cox043. https://doi.org/10.1093/conphys/cox043

Culina, A., Berg, I. van den, Evans, S., & Sánchez-Tójar, A. (2020). Low availability of code in ecology: A call for urgent action. *PLOS Biology*, *18*(7), e3000763. https://doi.org/10.1371/journal.pbio.3000763

Davidson, A. D., & Hewitt, C. L. (2014). How often are invasion-induced ecological impacts missed? *Biological Invasions*, *16*(5), 1165–1173. https://doi.org/10.1007/s10530-013-

0570-4

Davis, A. J., & Kay, S. (2023). Writing statistical methods for ecologists. *Ecosphere*, *14*(5), e4539. https://doi.org/10.1002/ecs2.4539

Federer, L. M., Belter, C. W., Joubert, D. J., Livinski, A., Lu, Y.-L., Snyders, L. N., & Thompson, H. (2018). Data sharing in PLOS ONE: An analysis of Data Availability Statements. *PLOS ONE*, *13*(5), e0194768. https://doi.org/10.1371/journal.pone.0194768

Filazzola, A., & Cahill Jr, J. F. (2021). Replication in field ecology: Identifying challenges and proposing solutions. *Methods in Ecology and Evolution*, *12*(10), 1780–1792. https://doi.org/10.1111/2041-210X.13657

Fraser, L. H., Henry, H. A., Carlyle, C. N., White, S. R., Beierkuhnlein, C., Cahill, J. F., Casper, B. B., Cleland, E., Collins, S. L., Dukes, J. S., Knapp, A. K., Lind, E., Long, R., Luo, Y., Reich, P. B., Smith, M. D., Sternberg, M., & Turkington, R. (2013). Coordinated distributed experiments: An emerging tool for testing global hypotheses in ecology and environmental science. *Frontiers in Ecology and the Environment*, *11*(3), 147–155. https://doi.org/10.1890/110279

Haddaway, N. R., Macura, B., Whaley, P., & Pullin, A. S. (2018). ROSES RepOrting standards for Systematic Evidence Syntheses: Pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. *Environmental Evidence*, *7*(1), 7. https://doi.org/10.1186/s13750-018-0121-7

Kambouris, S., Wilkinson, D. P., Smith, E. T., & Fidler, F. (2024). Computationally reproducing results from meta-analyses in ecology and evolutionary biology using shared code and data. *PLOS ONE*, *19*(3), e0300333. https://doi.org/10.1371/journal.pone.0300333

Kast, S., Shelton, B., & Pither, J. (2023, February 15). *Mycorrizhal Research Reproducibility Review*. Open Science Framework. https://doi.org/10.17605/OSF.IO/9BV8Q

Katz, G. L., & Shafroth, P. B. (2003). Biology, ecology and management of Elaeagnus angustifolia L. (Russian olive) in western North America. *Wetlands*, *23*(4), 763–777.

https://doi.org/10.1672/0277-5212(2003)023[0763:BEAMOE]2.0.CO;2

Kelly, C. D. (2019). Rate and success of study replication in ecology and evolution. *PeerJ*, *7*, e7654. https://doi.org/10.7717/peerj.7654

Knollová, I., Chytrý, M., Bruelheide, H., Dullinger, S., Jandt, U., Bernhardt-Römermann, M., Biurrun, I., de Bello, F., Glaser, M., Hennekens, S., Jansen, F., Jiménez-Alfaro, B., Kadaš, D., Kaplan, E., Klinkovská, K., Lenzner, B., Pauli, H., Sperandii, M. G., Verheyen, K., … Essl, F. (2024). ReSurveyEurope: A database of resurveyed vegetation plots in Europe. *Journal of Vegetation Science*, *35*(2), e13235. https://doi.org/10.1111/jvs.13235

Lalk, S., Hartshorn, J., & Coyle, D. R. (2021). Invasive Woody Plants and Their Effects on Arthropods in the United States: Challenges and Opportunities. *Annals of the Entomological Society of America*, *114*(2), 192–205. https://doi.org/10.1093/aesa/saaa054

Lamberink, H. J., Otte, W. M., Sinke, M. R. T., Lakens, D., Glasziou, P. P., Tijdink, J. K., & Vinkers, C. H. (2018). Statistical power of clinical trials increased while effect size remained stable: An empirical analysis of 136,212 clinical trials between 1975 and 2014. *Journal of Clinical Epidemiology*, *102*, 123–128. https://doi.org/10.1016/j.jclinepi.2018.06.014

Mologni, F., Moffat, C. E., & Pither, J. (2023a). Collating existing evidence on cumulative impacts of invasive plant species in riparian ecosystems of British Columbia, Canada: A systematic map protocol. *Environmental Evidence*, *12*(1). https://doi.org/10.1186/s13750-023-00320-3

Mologni, F., Moffat, C. E., & Pither, J. (2023b, December 14). *Collating existing evidence on cumulative impacts of invasive plant species in riparian ecosystems of British Columbia, Canada: A systematic map protocol*. PROCEED. https://doi.org/10.57808/proceed.2023.28

Munafò, M. R., Nosek, B. A., Bishop, D. V. M., Button, K. S., Chambers, C. D., Percie du Sert, N., Simonsohn, U., Wagenmakers, E.-J., Ware, J. J., & Ioannidis, J. P. A. (2017). A manifesto for reproducible science. *Nature Human Behaviour*, *1*(1), 0021. https://doi.org/10.1038/s41562-016-0021

National Academies Of Sciences, Engineering, And Medicine. (2019). *Reproducibility and Replicability in Science*. The National Academies Press. https://doi.org/10.17226/25303

Nosek, B. A., Hardwicke, T. E., Moshontz, H., Allard, A., Corker, K. S., Dreber, A., Fidler, F., Hilgard, J., Struhl, M. K., Nuijten, M. B., Rohrer, J. M., Romero, F., Scheel, A. M., Scherer, L. D., Schönbrodt, F. D., & Vazire, S. (2022). Replicability, Robustness, and Reproducibility in Psychological Science. *Annual Review of Psychology*, *73*(Volume 73, 2022), 719–748. https://doi.org/10.1146/annurev-psych-020821-114157

O'Dea, R. E., Parker, T. H., Chee, Y. E., Culina, A., Drobniak, S. M., Duncan, D. H., Fidler, F., Gould, E., Ihle, M., Kelly, C. D., Lagisz, M., Roche, D. G., Sánchez-Tójar, A., Wilkinson, D. P., Wintle, B. C., & Nakagawa, S. (2021). Towards open, reliable, and transparent ecology and evolutionary biology. *BMC Biology*, *19*(1), 68. https://doi.org/10.1186/s12915-021-01006-3

Open Science Collaboration. (2015). Estimating the reproducibility of psychological science. *Science*, *349*(6251), aac4716. https://doi.org/10.1126/science.aac4716

Packer, J. G., Meyerson, L. A., Richardson, D. M., Brundu, G., Allen, W. J., Bhattarai, G. P., Brix, H., Canavan, S., Castiglione, S., Cicatelli, A., Čuda, J., Cronin, J. T., Eller, F., Guarino, F., Guo, W.-H., Guo, W.-Y., Guo, X., Hierro, J. L., Lambertini, C., … Pyšek, P. (2017). Global networks for invasion science: Benefits, challenges and guidelines. *Biological Invasions*, *19*(4), 1081–1096. https://doi.org/10.1007/s10530-016-1302-3

Parker, T. H., Bowman, S., Nakagawa, S., Gurevitch, J., Mellor, D. T., Rosenblatt, R., & DeHaven, A. C. (2016). *Tools for Transparency in Ecology and Evolution (TTEE)*. https://doi.org/10.17605/OSF.IO/G65CB

Parker, T. H., Forstmeier, W., Koricheva, J., Fidler, F., Hadfield, J. D., Chee, Y. E., Kelly, C. D., Gurevitch, J., & Nakagawa, S. (2016). Transparency in Ecology and Evolution: Real Problems, Real Solutions. *Trends in Ecology & Evolution*, *31*(9), 711–719. https://doi.org/10.1016/j.tree.2016.07.002

Parker, T. H., Griffith, S. C., Bronstein, J. L., Fidler, F., Foster, S., Fraser, H., Forstmeier, W., Gurevitch, J., Koricheva, J., Seppelt, R., Tingley, M. W., & Nakagawa, S. (2018). Empowering peer reviewers with a checklist to improve transparency. *Nature Ecology & Evolution*, *2*(6), 929–935. https://doi.org/10.1038/s41559-018-0545-z

Parker, T. H., & Yang, Y. (2023). Exaggerated effects in ecology. *Nature Ecology & Evolution*, *7*(9), Article 9. https://doi.org/10.1038/s41559-023-02156-z

Pither, J. (2024). *Example reproducible workflow*.

Popovic, G., Mason, T. J., Drobniak, S. M., Marques, T. A., Potts, J., Joo, R., Altwegg, R., Burns, C. C. I., McCarthy, M. A., Johnston, A., Nakagawa, S., McMillan, L., Devarajan, K., Taggart, P. L., Wunderlich, A., Mair, M. M., Martínez-Lanfranco, J. A., Lagisz, M., & Pottier, P. (2024). Four principles for improved statistical ecology. *Methods in Ecology and Evolution*, *15*(2), 266–281. https://doi.org/10.1111/2041-210X.14270

Popovic, G., Mason, T. J., Drobniak, S. M., Marques, T. A., Potts, J., Joo, R., Altwegg, R., Burns, C. C. I., McCarthy, M. A., Johnston, A., Nakagawa, S., McMillan, L., Devarajan, K., Taggart, P. L., Wunderlich, A., Mair, M. M., Martínez-Lanfranco, J. A., Lagisz, M., & Pottier, P. (2024). Four principles for improved statistical ecology. *Methods in Ecology and Evolution*, *15*(2), 266–281. https://doi.org/10.1111/2041-210X.14270

Price, E. P. F., Spyreas, G., & Matthews, J. W. (2018). Biotic homogenization of regional wetland plant communities within short time-scales in the presence of an aggressive invader. *Journal of Ecology*, *106*(3), 1180–1190. https://doi.org/10.1111/1365-2745.12883

Ridley, F. A., Hickinbotham, E. J., Suggitt, A. J., McGowan, P. J. K., & Mair, L. (2022). The scope and extent of literature that maps threats to species globally: A systematic map. *Environmental Evidence*, *11*(1), Article 1. https://doi.org/10.1186/s13750-022-00279-7

Riordan-Short, E., Pither, R., & Pither, J. (2023). Four steps to strengthen connectivity modeling. *Ecography*, *2023*(11), e06766. https://doi.org/10.1111/ecog.06766

Roche, D. G., Kruuk, L. E. B., Lanfear, R., & Binning, S. A. (2015a). Public Data Archiving in Ecology and Evolution: How Well Are We Doing? *PLOS Biology*, *13*(11), e1002295. https://doi.org/10.1371/journal.pbio.1002295

Roche, D. G., Kruuk, L. E. B., Lanfear, R., & Binning, S. A. (2015b). Public Data Archiving in Ecology and Evolution: How Well Are We Doing? *PLOS Biology*, *13*(11), e1002295. https://doi.org/10.1371/journal.pbio.1002295

Rowe, J. C., Duarte, A., Pearl, C. A., McCreary, B., Galvan, S. K., Peterson, J. T., & Adams, M. J. (2019). Disentangling effects of invasive species and habitat while accounting for observer error in a long-term amphibian study. *Ecosphere*, *10*(4), e02674. https://doi.org/10.1002/ecs2.2674

Roy, H. E., Pauchard, A., Stoett, P., Renard Truong, T., Bacher, S., Galil, B. S., Hulme, P. E., Ikeda, T., Sankaran, K., McGeoch, M. A., Meyerson, L. A., Nuñez, M. A., Ordonez, A., Rahlao, S. J., Schwindt, E., Seebens, H., Sheppard, A. W., & Vandvik, V. (2024). *IPBES Invasive Alien Species Assessment: Summary for Policymakers* (Version 3). Zenodo. https://doi.org/10.5281/ZENODO.7430692

Strømme, C. B., Lane, A. K., Halbritter, A. H., Law, E., Nater, C. R., Nilsen, E. B., Boutouli, G. D., Egelkraut, D. D., Telford, R. J., Vandvik, V., & Cotner, S. H. (2022). Close to open—Factors that hinder and promote open science in ecology research and education. *PLOS ONE*, *17*(12), e0278339. https://doi.org/10.1371/journal.pone.0278339

van Kleunen, M., Pyšek, P., Dawson, W., Essl, F., Kreft, H., Pergl, J., Weigelt, P., Stein, A., Dullinger, S., König, C., Lenzner, B., Maurel, N., Moser, D., Seebens, H., Kartesz, J., Nishino, M., Aleksanyan, A., Ansong, M., Antonova, L. A., … Winter, M. (2019). The

Global Naturalized Alien Flora (GloNAF) database. *Ecology*, *100*(1), e02542. https://doi.org/10.1002/ecy.2542

Yahdjian, L., Sala, O. E., PiÑEiro-Guerra, J. M., Knapp, A. K., Collins, S. L., Phillips, R. P., & Smith, M. D. (2021). Why Coordinated Distributed Experiments Should Go Global. *BioScience*, *71*(9), 918–927. https://doi.org/10.1093/biosci/biab033

Yang, Y., Hillebrand, H., Lagisz, M., Cleasby, I., & Nakagawa, S. (2022). Low statistical power and overestimated anthropogenic impacts, exacerbated by publication bias, dominate field studies in global change biology. *Global Change Biology*, *28*(3), 969–989. https://doi.org/10.1111/gcb.15972

Yang, Y., Sánchez-Tójar, A., O'Dea, R. E., Noble, D. W. A., Koricheva, J., Jennions, M. D., Parker, T. H., Lagisz, M., & Nakagawa, S. (2023). Publication bias impacts on effect size, statistical power, and magnitude (Type M) and sign (Type S) errors in ecology and evolutionary biology. *BMC Biology*, *21*(1), 71. https://doi.org/10.1186/s12915-022-01485-y

Zedler, J. B., & Kercher, S. (2004). Causes and Consequences of Invasive Plants in Wetlands: Opportunities, Opportunists, and Outcomes. *Critical Reviews in Plant Sciences*, *23*(5), 431–452. https://doi.org/10.1080/07352680490514673

Box 1 Definitions of reproducible and replicable according to the National Academies of Sciences, Engineering, and Medicine (2019) and Nosek et al. (2022)

Reproducible: The ability to independently re-do the research using the same data and materials and obtain the same results.

Replicable: The ability to independently re-do the research using new materials and data and obtain consistent results.

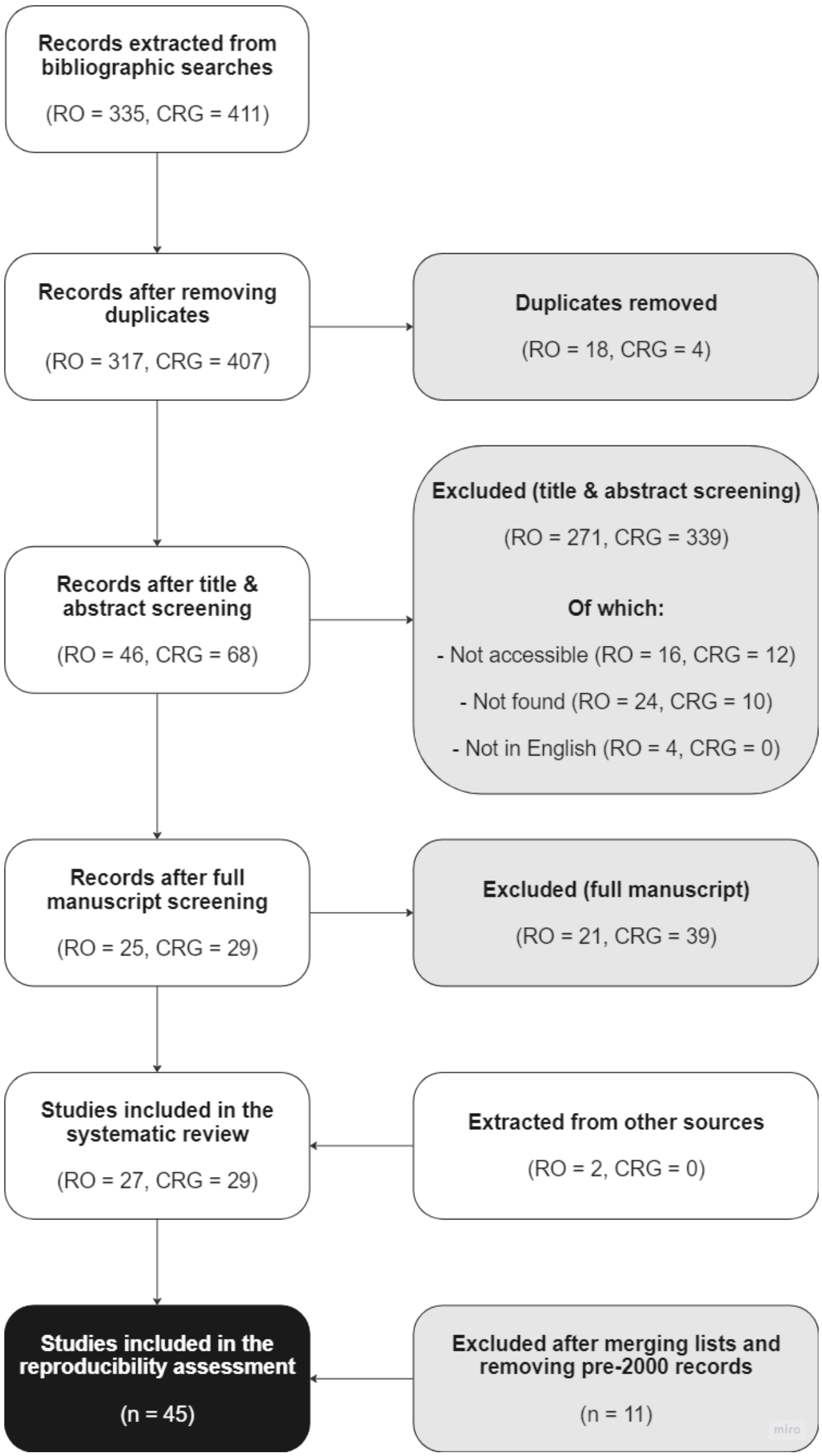
Figure Captions

Figure 1 Screening process following ROSES reporting standards (Haddaway et al., 2018). ‘Records extracted from bibliographic searches’ refers to studies extracted from WOS, CABI and reviews identified from those sources. “Extracted from other sources” refers to studies not identified through the systematic search of bibliographic databases.

Figure 2 Number of studies (grey bars) and average score (black line) by publication year.

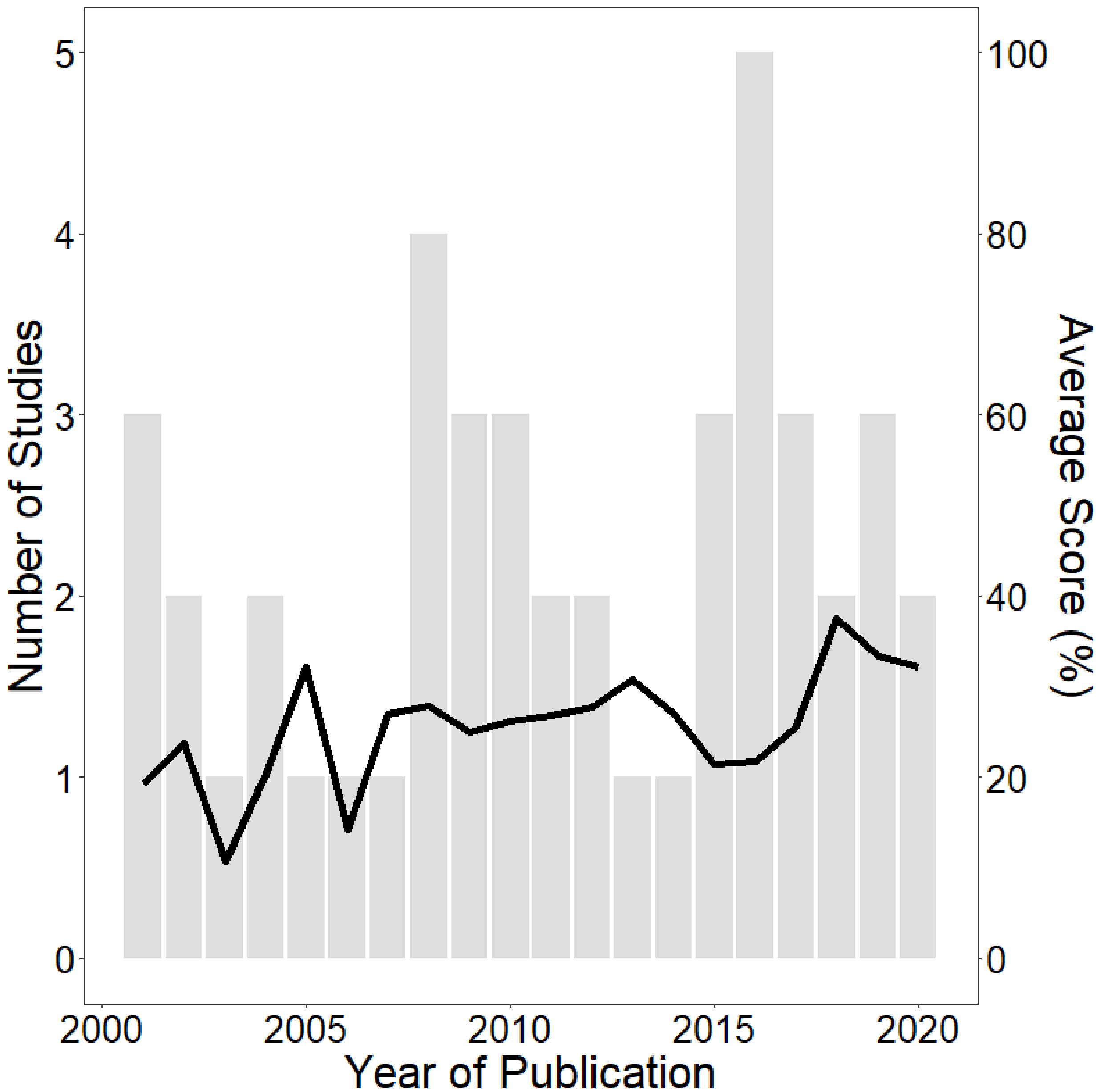
Figure 3 Plots displaying average scores by item category. Colours indicate *overlooked* (white, < 0.2), *in progress* (grey, 0.2-0.8), and *addressed* (black, >0.8) items.

Figure 1



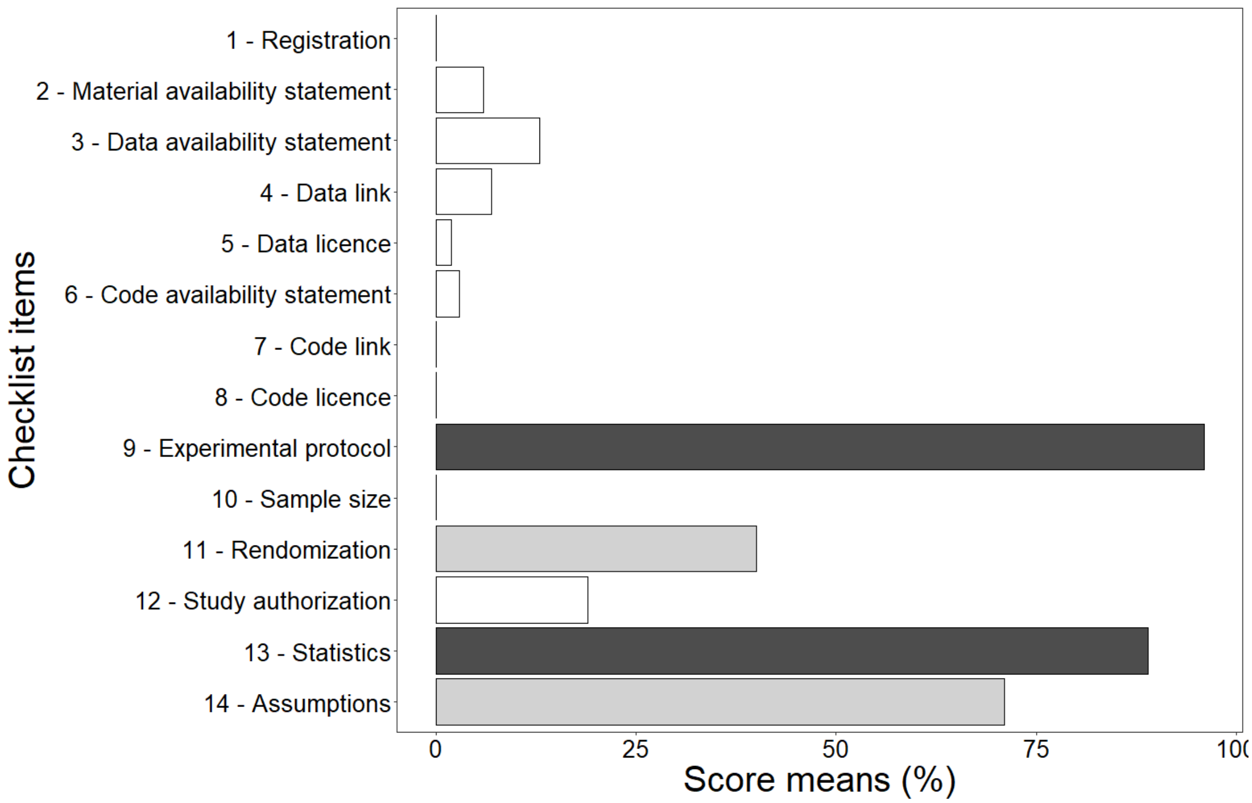
Records extracted from bibliographic searches
(RO = 335, CRG = 411)
Records after removing duplicates
(RO = 317, CRG = 407)
Duplicates removed
(RO = 18, CRG = 4)
Excluded (title & abstract screening)
(RO = 271, CRG = 339)
Of which:
- Not accessible (RO = 16, CRG = 12)
- Not found (RO = 24, CRG = 10)
- Not in English (RO = 4, CRG = 0)
Records after title & abstract screening
(RO = 46, CRG = 68)
Records after full manuscript screening
(RO = 25, CRG = 29)
Excluded (full manuscript)
(RO = 21, CRG = 39)
Studies included in the systematic review
(RO = 27, CRG = 29)
Extracted from other sources
(RO = 2, CRG = 0)
Studies included in the reproducibility assessment
(n = 45)
Excluded after merging lists and removing pre-2000 records
(n = 11)

Figure 2



Number of Studies
Average Score (%)
Year of Publication
0
1
2
3
4
5
0
20
40
60
80
100
2000
2005
2010
2015
2020

Figure 3



Checklist items
1 - Registration
2 - Material availability statement
3 - Data availability statement
4 - Data link
5 - Data licence
6 - Code availability statement
7 - Code link
8 - Code licence
9 - Experimental protocol
10 - Sample size
11 - Rendomization
12 - Study authorization
13 - Statistics
14 - Assumptions
0
25
50
75
100
Score means (%)

Data availability statement

Data and code are available at https://doi.org/10.5281/zenodo.14288882.

Acknowledgments

We thank Mathew Vis-Dunbar (UBC librarian) for providing valuable comments.

Funding

FM is funded by the Ministry of Forests, British Columbia, Canada, and by the Irving K. Barber Faculty of Science at the Okanagan campus of UBC. JP acknowledges financial support from the Natural Science and Engineering Council of Canada (Discovery Grant 2020-43906543). Open access funding provided by the University of Vienna.

Competing interests

The authors declare that they have no competing interests.

Supplementary material

Appendix 1 - Full scoring rubric.

Appendix 2 - List of studies included in this article and associated scores by rubric item.

Appendix 3 - Supplementary information

Appendix 1 – Checklist of Open Science Best Practices

Scoring

0 = Not completed
1 = Partially completed (does not complete all aspects of a given criterion)
2 = Fully completed
NA = This criterion is not relevant

Criteria

Pre-Registration

1. Pre-Registration: Was the study pre-registered? Are protocol deviations/changes from the pre-registration fully described (e.g. experimental procedures)? (1 point each question)

Data, Methods, and Materials Availability

Note: A proper availability statement is a dedicated section that tries to improve the reproducibility of a manuscript by stating what data/code/materials were used during the study and where said data/code/materials can be found/obtained. Availability statements almost always have a dedicated header.

Note: The "code availability statement" refers to newly generated custom computer code (or the software or mathematical algorithm or LCA models).

2. Material_Availability[1]: Is there a materials availability statement (materials to include in a material availability statement are: plants, microbe strains, cell lines, primary cell cultures, and primers, as well as all unique chemical and biological materials, including commercially and non-commercially obtained materials, newly created materials, and unique specimens)?
    a. Sequence_Availability: Is there an accession number in repository or a supplier name, catalog number, clone number, or RRID for DNA/RNA sequences? Is metadata (e.g. hosts, source, collection location, etc.) available for DNA/RNA sequences?
    b. Plant_Availability: If plants were used, are the species, strain, ecotype, cultivar and source (including location for collected wild specimens) provided where relevant? Is there a unique accession number (if available)?

3. Data_Availability: Is there a data availability statement?

[1] Points are given even if material availability is discussed in the text, rather than as a separate section.

4. Data_Link: Is there an accession number or DOI or URL (data)?

5. Data_License: If there are newly created datasets, are licensing details for said datasets provided?

6. Code_Availability: Is there a code availability statement (Often included in data availability statement)?

7. Code_Link: Is there an accession number or DOI or URL (code)?

8. Code_License: If there is newly created code, are licensing details for said code provided?

9. Experimental_Protocol: Were detailed step-by-step experimental protocols made available to allow for replication? Are experimental protocols sufficiently described to allow for replication?

Experimental study design

10. Sample_Size: Is there a description of sample size/replicate determination (e.g., a priori power analysis)?

11. Randomization: Do the authors state if randomization occurred and justify why or why not? (1 point each question)

12. Study_Authorization: If the study involves field sampling, do the authors state if relevant permits were obtained and provide details of authority approving study? If none were required, is there an explanation?

Data Analysis

13. Statistics: Do the authors describe their use of statistical tests and justify their choice of tests?

14. Assumptions: Are appropriate assumptions of the applied statistical tests discussed

Appendix 3

Figure S1 Plots displaying scores by item category. First is the average of each score. Colours indicate *overlooked* (white, < 20%), *in progress* (grey, 20-80%), and *addressed* (black, >80%) items. Then, scores over time are illustrated.