Title: Supporting study registration to reduce research waste

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Abstract

Research suffers from many inefficiencies. These lead to much research being avoidably wasted, with no or limited value to the end user (e.g. an estimated 82-89% of ecological research, and 85% of medical research). Here, we argue that the quality and impact of ecological research could be drastically improved by registration: pre-registration, and registered reports. However, without a coordinated action of the overall research support and publishing system, the transition to more registrations and their impact on the research quality will be very slow, if anything. In this perspective we envision a registration system that would best serve the field of ecology. This system partly corresponds to solutions already available in other fields. However, we suggest several novel aspects that a system of registration, especially that of pre-registration, should offer if it were to truly make a substantial contribution to increasing quality and reducing waste in ecological research. We survey and review the evidence from other fields on whether registration reduces research waste. The evidence largely comes from medicine, where registries of studies have been in substantial use since 2000. With this Perspective we specifically aim to encourage funders, publishers, and research institutions to support researchers in adopting registration. To facilitate support, we suggest short- and long-term actions that could increase registration in ecology and reduce research waste.

Introduction

Estimates of avoidable waste in ecological research are high (82%-89%[1], based on 10 464 ecological studies). In addition to the waste of research funds, valuable information that could have otherwise been used to increase knowledge, guide future research, and inform interventions and policies, is also lost. Research waste is particularly worrying in ecology, which is at best modestly funded, and plays a central role in solving global challenges and reaching the Sustainable Development Goals[2]. Research waste has also been estimated in health research[3], with 85% of research being wasted (details in Table 1).

Three main components of research waste are: 1) unpublished research: research projects that never publish a single result (or a public dataset), 2) low quality studies (e.g. inappropriate data collection design, incorrect data analysis), and 3) under-reported results in published studies (e.g. a p-value without an associated effect size, unspecified sample size). Purgar et al. 2022[1] estimated that around 45% of funded research projects, thesis chapters, and documents in ecology were never published in a scientific journal, and therefore have limited or no visibility to the end users (other researchers, policy makers etc). Further, Purgar et al. 2022[1], estimated that 67% of studies in ecology were poorly planned with design or analysis flaws, and 41% of published results were under-reported. Such underreported results are uninformative, or even misinformative.

All the actors involved in the research system (funders, publishers, research institutions, researchers) could benefit from prioritising waste reduction. There are ample pathways to reduce waste, and many include open science practices. For example, open data could reduce research waste caused by improper analysis. This is because a more appropriate analysis can be applied to the dataset after the study is published. Such open data is now mandated by an increasing number of funders (e.g. Directive (EU) 2019/1024[4], US policy guidance[5]) and publishers (e.g. American Naturalist[6], OIKOS[7], Ecology Letters[8], etc.). Adherence to reporting guidelines (e.g. PRISMA-EcoEvo[9] and ROSES[10]) is another way to avoid waste, as these ensure sufficient reporting of results and methods. The aforementioned open science related changes in ecology have gained substantial visibility to researchers, funders, and publishers (e.g. increase in journal mandatory or encouraged code-sharing policies[11]; improvement in the completeness and reusability of ecology and evolution datasets[12]). However, another practice that can drastically reduce waste, but in ecology has received less attention and is almost never used is registration of studies.

In this Perspective we argue that registration of studies (both pre-registration[13–15] and registered reports[16,17]) - could substantially reduce research waste in ecology (and other fields). This is because registration of the study could allow for early detection of issues in study design and analysis, reduce questionable research practices, reduce publication bias, improve the quality of reporting in publications, and expose the study results even if the study is not published in a journal (see Table 1). Registration also leads to higher transparency and facilitates the identification of modifications (justified and unjustified ones) to the original study plan and reporting. We thus look into the existing evidence (from other fields) of the benefits of registration to reducing research waste. The evidence largely comes from medicine, the field where registries of clinical trials have been in substantial use since at least 2000[18,19], and registered reports since 2013[16].

The system of registration for ecology we envision has some similarities with existing systems. However, we also suggest several novel aspects that a system of registration, especially that of pre-registration, should offer if it was to truly make a substantial contribution to increasing quality of, and reducing waste in, ecological research. To implement such a system and increase the application of registration in ecology, we list actions that should be taken by funders, publishers, and research institutions and include: building support systems for registration (infrastructures, tools, experts), providing education and training of researchers and support stuff, and introduction of new metrics to measure academic success[20]. We also highlight potential challenges in transitioning to an era of higher application of registration in ecological research. Here, we take lessons from medicine, where some positive changes toward better quality of clinical trials have been achieved, yet registration is still not ubiquitous nor free of issues.

Table 1**.** *Research waste components, as estimated in medicine*[3] *and ecology*[1]*, and the potential effects of registration (registered reports and pre-registration) in reducing these. A potential benefit not stated in the table is that registration may increase the availability of data and software if pre-registration would require adding the data and software management plans. Data (and software) could then be used to reduce research waste at each of its main components.*

Causes of research waste	**Estimates from Medicine*** ([3] and Lancet 2014 series[21–25]) Based on follow up of registered trials and all studies approved by ethics committees, previous meta-studies on quality of design in clinical trials and meta-studies on quality of reporting	**Estimates from Ecology**[1] Based on meta-analysis of 43 effect sizes from 33 meta-studies that have already estimated different components of waste (based on overall 10 464 studies).	**Potential effect of Registration**
Low quality studies	50% of studies are designed without reference to systematic reviews of existing evidence Over 50% of studies fail to take adequate steps to reduce biases (e.g. unconcealed treatment allocation)	67% (95% CI 66-68%) of studies poorly planned. Issues appear in -the data collection design (e.g. experiments do not have control group) - data analysis (e.g. applying incorrect statistical analysis)	Improves study quality as it allows for early detection of study planning issues (in data collection and analysis) if a study registration is reviewed by experts
Under-reported results in published studies	Over 30% of trial interventions are not sufficiently described Over 50% of planned study outcomes are not reported	41% (95%CI 39-43%) of results in published articles are under-reported (e.g. do not provide sample size, effect size, or measure of uncertainty)	Improves reporting in published studies by templates and guidelines that highlight important components of the methodological process to be reported (e.g. sample size)
Unpublished research	Over 50% of studies remain unpublished (estimated based on conference abstracts that made it	45% (95% CI 44-47%) of research is unpublished (estimated based on	Reduces publication bias (e.g. results can be published regardless of

	to full publication, registeret RTC that were published, grey literature)	unpublished projects, unpublished theses chapters, and grey literature) - causes include publication bias, lack of time, and low-quality of studies	statistical significance of results and effect size magnitude and direction for registered reports), publication of results in registries is independent of whether study is published in a journal.

* Authors also assessed the relevance of research questions to clinicians and patients, which was not done in ecology - where it is more difficult to determine the relevance of research.

Pre-registration and registered reports in ecology

The research plan can be time-stamped prior to the research conduct. This is commonly done via one of the two related processes: (a) *pre-registration* where the protocol is posted in a registry (repository) independent of its eventual publication, and (b) *registered reports* where the protocol is peer-reviewed by a journal that will eventually publish the results (see Fig. 1). Both options have value in improving research quality and bring different pros and cons.

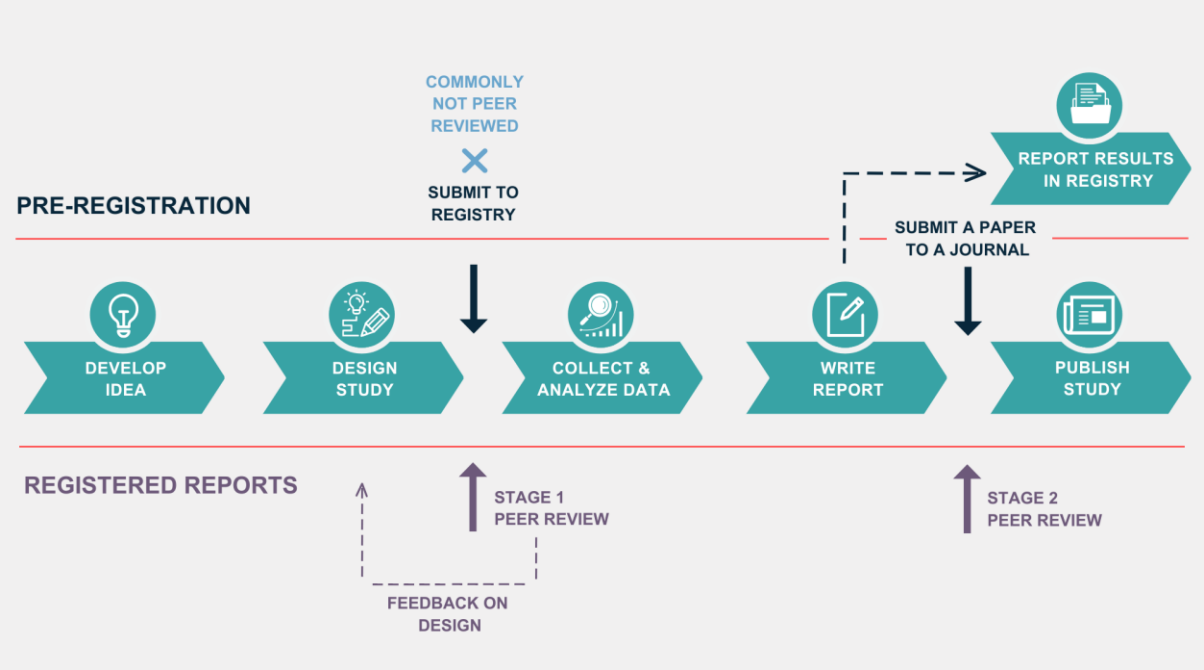

Figure 1. *The main pathways of registration: pre-registration and registered reports (RR). Both pathways involve the same principle of time-stamping the original research protocol (hypotheses, study design etc.) prior to data collection (or before viewing the data if working with pre-existing data) and analysis. In RR, this involves a peer review of the research protocol, while for pre-registration the protocol is submitted to a registry but generally not peer-reviewed. The results of the study (after data collection and analysis) are either submitted to the journal (for the first round of review for a pre-registered study, or a second round for an RR). Results of pre-registered studies can also be added to a registry, regardless of whether a study was formally published or not. This figure is inspired by: Center for Open Science (https://www.cos.io/initiatives/registered-reports, under CC BY 4.0).*

Pre-registration is a publicly documented research plan (e.g. questions, hypotheses, data collection plan, analysis plan) that is registered before data collection starts, before viewing the data if working with preexisting data, or before research results are known[13–15]. This can be done by storing the study plan in a (commonly read-only) public repository, such as OSF Registries (https://help.osf.io/article/145-preregistration) or the National Library of Medicine's Clinical Trials Registry (https://clinicaltrials.gov/). Researchers have the option to make pre-registration publicly accessible immediately or after an embargo period (https://help.osf.io/article/158-create-a-preregistration). As pointed out by[15], preregistration "reduces the risk of bias by encouraging outcome-independent decision-making and increases transparency, enabling others to assess the risk of bias and calibrate their confidence in research outcomes". Note that in medicine the term 'pre-registration', is not used, but rather 'registration'. However, within the manuscript we use term registration to encompass both pre-registration and registered reports.

Results of pre-registered studies are sometimes added to the study pre-registration upon the study completion (regardless of whether the study was published). For clinical trials, this is often required by international policies (e.g. WMA Declaration of Helsinki - Ethical Principles for Medical Research Involving Human Subjects[26]), funders (e.g. NIH Policy on the Dissemination of NIH-funded Clinical Trial Information[27]), journals (e.g. ICMJE[28]), and others (please see: Why Should I Register and Submit Results? - ClinicalTrials.gov and History, Policies, and Laws - ClinicalTrials.gov). However, many funders still do not explicitly mandate registration (e.g. among 21 medical research funders in Europe only 14 mandate prospective trial registration[29]). Further, registration policies are not always followed, as we will discuss later. Pre-registration is likely uncommon in ecology: while there is no estimate of how much of the primary literature is registered, only 3% of systematic reviews and meta-analyses published in ecology and evolutionary biology have been pre-registered[9].

Registered reports[16,17] are a publication format where peer-review and editorial approval of a study's design and methods happen before data collection (stage 1, note that for systematic reviews 'data collection' refers to 'access to data already collected by others') or analysis if working on already collected data. Once the research is completed, authors submit the final article containing results and discussion (stage 2), which undergoes additional peer-review to ensure that the study follows the original protocol, and transparently reports and justifies any deviation from the protocol. Registered reports' acceptance is independent of the results obtained, and it depends on the relevance of the research topic, thorough development of the research questions/hypotheses, and the robustness of the methodological approach. This format not only promotes methodological rigour but also helps to reduce publication bias and enhance transparency in science[30].

An increasing number of journals that publish ecological and evolutionary biology research are introducing registered reports. As of August 2023, 24 such journals (see Supplementary Table 1) offer registered reports, and include Nature Ecology and Evolution, Ecology and Evolution (Wiley), Ecological Solutions and Evidence (Wiley), and PLOS ONE. They provide author guidelines on how to submit and format reports, have implemented rigorous review processes and standards for publishing registered reports in ecology. However very few registered reports have been published (see Supplementary Table 1).

Decreasing research waste via registration (pre-registration or registered reports)

Registration could reduce several components of research waste, and improve study quality and thus robustness and reliability of results (see Table 1). Meta-studies, mostly done on clinical trials, show that published studies that were pre-registered have higher quality of methodological design[31], lower risk of bias[32,33], and are more likely to report important methodological details (e.g. [34]). Pre-registered studies were also found to report smaller effect sizes and fewer statistically significant effect sizes (e.g. [35]) that were less often in the desired direction (e.g. [36]) - such results are expected under lower rates of questionable research practices. Meta-studies that compared registered reports with non-registered reports detected similar patterns (see Supplementary Table 2 for details on these meta-studies).

However, meta-studies also show that pre-registrations are only partially effective in improving study quality and completeness of reporting, and in reducing publication bias and outcome reporting bias. Pre-registrations are sometimes not of high quality[31,37], and published studies often differ from their pre-registered versions in methodology (e.g. [38]), outcome measures (e.g. [39]), and result reporting[40,41]. This outcome measure and result reporting bias is often (but not always, e.g. [39]) in favour of statistically significant results, larger effects, and effects that support hypotheses that were tested (see references in Supplementary Table 3). Thus, the benefits we list below are the best-case scenario. Achieving these benefits would require additional changes to the overall system of registration (including incentives, support, etc.) as we discuss in later sections.

To provide examples of how registration could reduce research waste, we summarise the findings of 26 meta-studies on the impact of pre-registration and registered reports on the methodological and reporting quality of research, and on the features of the results reported in published studies. These meta-studies were mostly conducted within the field of medicine (N=19), and psychology (N=6), while one covered both fields. Most of the meta-studies compared published pre-registered studies, with those that were not pre-registered (N=21), and 5 compared registered reports with standard literature (see Supplementary Table 2 for details on these studies and effects they have detected). We obtained these references through an exploratory survey (details of the procedure are in the Supplementary Methods). We might have missed some studies, but these omissions should not be biased towards meta-studies with certain results, given our search terms (see Supplementary Methods). We also did not conduct a critical appraisal of the included meta-studies (assess the risk of bias, and potential co-founders). For example, researchers who decide to submit a registered report are also likely to already use practices that improve the robustness of research (e.g. blinding) compared to other researchers. The reference list we obtained could serve as a starting point for a systematic review of the topic.

Together with the benefits that we list below we also highlight some changes to the current system, especially of pre-registration, that would allow for the mentioned benefits to be best realised.

(1) *Improve the study planning (including a reduction in QRPs*)

Most of the wasted research in ecology (estimated 67%[1]) comes from poorly planned studies (suboptimal study design or inappropriate analytical procedures). Pre-registration could drastically improve study quality if registered studies were open (or even required) for quality checks by statisticians and other experts. They could also be opened to stakeholders that

might be impacted by research (e.g. farmers). This could improve the study design (e.g. data collection) and analysis, and increase the relevance of the study to the stakeholders. However, studies in registries are almost never open for quality checks or other types of input (with rare exceptions such as Australian New Zealand Clinical Trials Registry: https://www.anzctr.org.au/Default.aspx, https://www.anzctr.org.au/docs/registration%20process%20flow%20chart.pdf). On the other hand, quality checks are already implemented via Stage 1 peer review in registered reports.

Even without external review, registration will likely improve study design if registration templates contain important elements that need to be considered when designing a study protocol (e.g. randomization, blinding). Meta-studies on clinical trials all show that pre-registered studies had higher methodological quality (two meta-studies), lower risk of bias (six meta-studies), and larger sample sizes (nine meta-studies) compared to non-registered studies (see Supplementary Table 2 for details). For example, Won et al. 2019[32] found that prospectively registered studies displayed a lower risk of bias in random sequence generation, allocation concealment, and selective outcome reporting. Only one meta-study we have detected in our exploratory survey examined the differences in methodological quality between registered reports and standard literature. Here, registered reports showed a more rigorous methodology, higher quality methodology, and better alignment between the research question and methodology[42].

(2) Reduce questionable research practices

Registration can reduce questionable research practices such as p-hacking. Results of published studies that were pre-registered have been shown to have smaller effect sizes (found in five of five meta-studies on the topic), less often support the hypothesis (found in four of five meta-studies), and have lower statistical significance (found if one meta-study) compared to published studies that were not pre-registered (see Supplementary Table 2 for details). For example, Schafer and Schwarz 2019[35] found that pre-registered studies in psychology (N=93) report smaller effects (median r = 0.16) compared to not pre-registered studies (N=900, median r = 0.36). Similar trends were found in four meta-studies that explored differences in results reported in registered reports with the results in standard literature. For instance, Brohmer et al. 2021[43] found that published studies reported larger effects (g = 0.42) than unpublished studies and published registered reports (g =-0.01).

(3) Reduce publication bias and increase the availability of study results

Estimated 45% of ecological research is never published[1]. Studies remain unpublished for many reasons including lack of time, low-quality work that is consequently not publishable, or publication bias[44,45]. Registration could reduce waste caused by any unpublished research and specifically counter publication bias. Registered reports do exactly this - results do not influence the acceptance nor publication of the manuscript. For example, Scheel et al 2021[46] compared the results of published registered reports with a random sample of hypothesis-testing studies from standard literature in psychology. They found that 96% of the standard literature (N=152) had positive results, whereas only 44% of the registered reports (N=71) had positive results, demonstrating the potential impact of registered reports in reducing publication bias (and questionable research practices).

Registries of pre-registered studies could also publish the results of the registered study, regardless of the study's publication in a journal. These results could then be accessible to

everyone via the registry where the study was pre-registered. In medicine, funders often mandate that results of clinical trials are published in registries (e.g. UK's Medical Research Council https://www.ukri.org/councils/mrc/, UK's National Institute for Health Research https://www.nihr.ac.uk/, or Germany's Federal Ministry of Education and Research https://www.bmbf.de/bmbf/en/home/home_node.html), leading to potentially more results being reported in the registries than published via journals. For example, primary outcomes have been reported for 72% (out of 905) studies registered at ClinicalTrials.gov compared to the literature published from these trials (22% of 905)[47]. The meta-studies from our explanatory survey generally detected consistent discrepancies in outcomes and results reported in published studies and their entry in the registry (see Supplementary Table 3).

A similar approach, where results of pre-registered studies would be available via registries, could be applied in ecology, drastically increasing the availability of results and the potential impact of studies not published in journals. Here, we note that the results in ecology come from a much larger variety of study designs compared to medicine, thus, reporting of results in registries could be of a free format (still following more general reporting guidelines).

(4) Improve reporting in published studies

Registration could reduce issues with underreporting of results such as reporting only a p-value without an associated effect size (estimated 41% of results are under-reported in ecology[1]). This is because pre-registration templates and guidelines clearly outline important components of the methodological process (e.g. sample size) that must be specified during pre-registration. Indeed, medical journal articles that were pre-registered have a better quality of methodological reporting than unregistered ones (see Supplementary Table 2). However, none of the meta-studies we obtained via our exploratory survey was on the completeness of result reporting (reporting on all important elements of results, such as effect size, sample size, and measure of uncertainty). At Stage 2 of the registered report, the authors are often encouraged to have a section "Deviations and Additions" to Stage 1. This section can make the process of science more authentic and honest as a scientific project almost always involves unplanned and unexpected changes.

(5) Increase the availability of data and software

While currently not commonly done, registrations (pre-registration and registered reports) could also include a short section on data and software management. This would likely improve the later availability of data and software, which would in turn eliminate some of the research waste. First, published raw data would eliminate the waste caused by studies that never publish any results because the data used in these studies could still be used by others. Second, raw data could reduce some of the issues with study planning. Notably, such data would enable applying correct analysis in published studies with incorrect analysis (estimated 47.1% of studies in ecology[48]). Third, raw data could be used to understand under-reported results (e.g. if an effect size published in a study lacks the sample size).

The above discussed benefits of registration translate into benefits to researchers. Further benefits to researchers are discussed elsewhere and include reduced workload down the line (e.g. when reporting the study methodology), greater transparency, searching and refining ideas, networking, and promoting trust within the community[49–52]. Registration could also potentiate sounder funding allocation, and savings in financial, human, and time resources (e.g.[49]). While costs of registration exist (e.g. time investment in creating registration), the

benefits should outweigh the costs, as found in a survey of 355 researchers[53]. Further, and as we discuss in the next section, funders and publishers could greatly reduce the cost of registration to researchers.

What could funders and publishers do?

The quantity and quality of registrations in ecology will increase when all the actors within the research system commit to a coordinated change. For example, mandating registration without proper incentives might lead to only an increase in the quantity but not the quality of registration (as we have seen for open data in ecology[54]). The important components of change include setting up the appropriate registration infrastructure, developing registration tools and templates, supporting and educating researchers, and changing incentives and setting up reasonable mandates (Fig. 2). We have examples from other fields (both successes and failures), chiefly clinical trials in medicine, to learn from. Clearly, ecological research is different from medical research, especially clinical trials, and thus would require its own, adjusted ways of pre-registration. Here, we concentrate on actions that funders, publishers, but also research institutes and universities could do to facilitate registration in ecology.

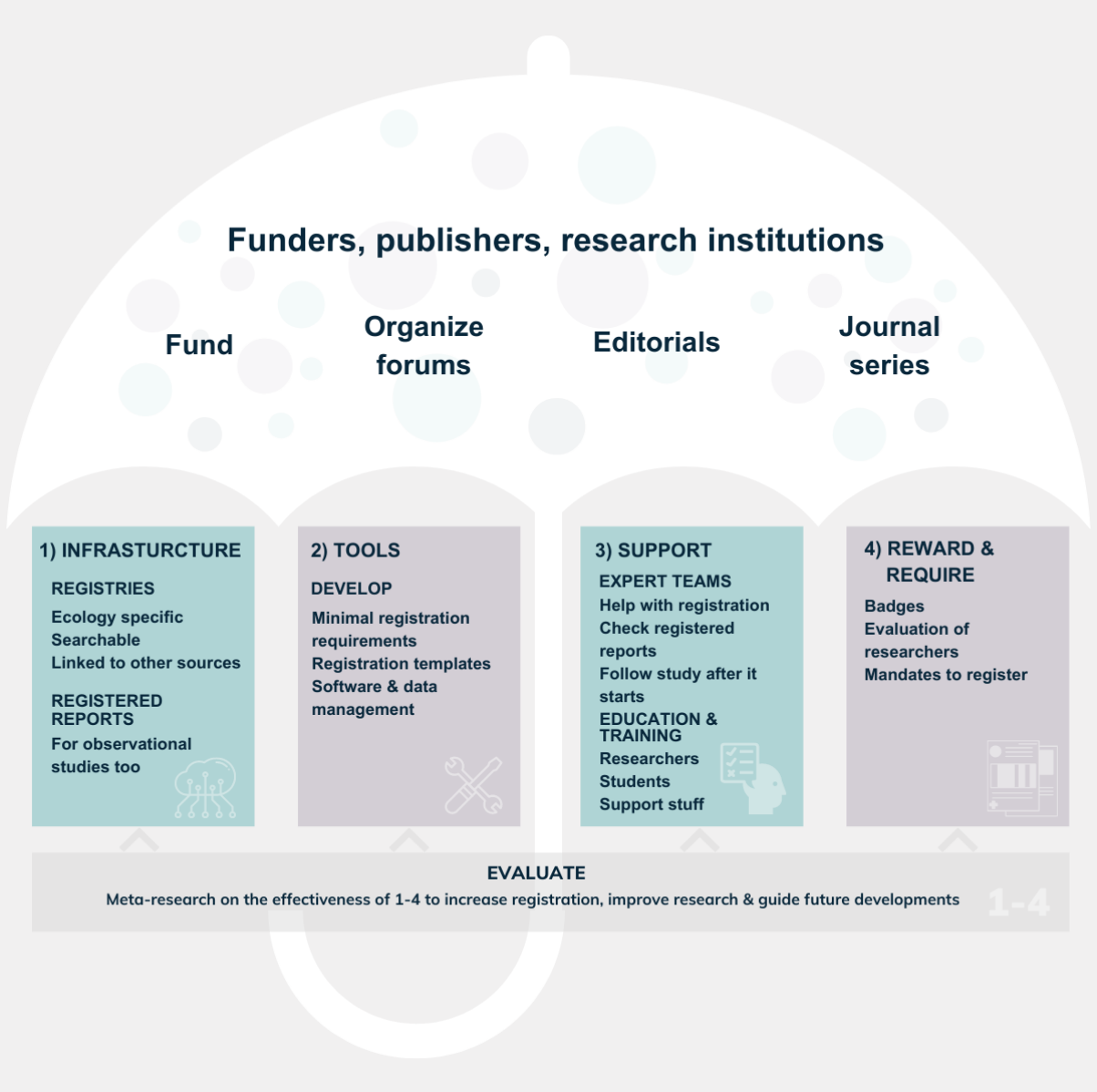

Figure 2. *To enable more registration and better quality registration in ecology, and boost the use of the information contained in the registries (e.g. use of results of unpublished, but registered studies), funders, publishers, and research institutes should aim to support the establishment of relevant infrastructures, create a better support system for scientists, introduce registration incentives and mandates, and support research to evaluate the effect of registration on the quality of research. As a start, we suggest more financial support for the change, organization of forums, publication of editorials, and even a journal series dedicated to the topic of registration in ecology.*

Infrastructure (and tools) to support pre-registration is relatively abundant in some fields (e.g. medicine[55]). However, there is no registry specific for ecological research (note that OSF recently started a Working Group[56] from a variety of scientific fields, including ecology, that aims to develop, curate and evaluate field-specific pre-registration templates). Funders should seek to support the development of such a registry, whose structure would reflect the specific needs of ecological studies (e.g. often observational rather than experimental). The registry

could be built de-novo, or based on existing infrastructure (e.g. OSF). We propose that such a registry should:

(i) allow for a modular type of registration, where different stages of a study can be pre-registered at different times. A typical pre-registration would include three main parts: research aims (including questions & hypotheses where relevant), a study design plan (e.g., target sample size, data collection procedures), and an analysis plan (e.g., statistical models). Such pre-registration shifts the burden of some work, such as analysis design, to earlier in a project, and this front-loading of work burden may be an obstacle to adoption for many. Therefore, we propose to lower the hurdle for embarking on pre-registration by making pre-registration modular. For example, hypotheses can be registered first, followed by a data collection protocol and set up later, and so on. Modules could be also made updatable. Although we would still encourage researchers to complete all three parts, modular registration would allow them to register just their aims or hypotheses (cf. [57]). Some modular solutions to connecting research components are offered by Octopus (https://www.octopus.ac/), while Research Equals (https://www.researchequals.com/) could be further developed for pre-registration.

(ii) allow for submitting the results of a study to a registry. For instance, ClinicalTrials.gov Protocol Registration and Results System (PRS) is a Web-based data entry system that enables users to submit results information for a registered study (https://classic.clinicaltrials.gov/ct2/manage-recs/submit-study). In this way, even if unpublished via a traditional route in a journal, study results are still available for potential users, and also counter publication bias.

(iii) provide a user-friendly search interface, and expose meta-data on registered studies to search engines and platforms. In this way, registries would enable the search of registered studies by third parties and the identification of work that has been conducted but remains unpublished via traditional routes. To our knowledge, such a system that is connected to search platforms has not been developed yet, and thus finding studies in registries requires searching in the registry itself.

Establishing registries of ecological studies should go in parallel with the development of the minimum registration requirements and registration templates (that would then be implemented by the registries). These requirements should ideally be worked out together with the research communities and might differ between different types of ecological research. Some examples of the minimum information for a registered study are WHO's Trial Registration Data Set (TRDS) for clinical trials (https://www.who.int/clinical-trials-registry-platform/network/who-data-set), or Preregistration Standards for Quantitative Research in Psychology (https://prereg-psych.org/index.php/rrp/templates) created by joint efforts of multi-society Preregistration Task Force (https://leibniz-psychology.org/en/news/detail/internationale-zusammenarbeit-prae-registrierungsvorlage-fuer-die-quantitative-forschung-in-der-psych-1). Further, we propose that pre-registrations and registered reports include data and software management plans, as data and software are a central part of the research conduct and research output.

Journals should become open to introducing registered reports as an article type. An increasing number of journals in ecology, listed in Supplementary Table 1, already accept registered reports and can be approached to share their experience. Society for Open,

Reliable, and Transparent Ecology and Evolutionary Biology has a journal liaison officer who can answer any question editors or others might have. We have checked (on the 15th of July 2023) the websites of 24 journals that offer registered reports for ecological research, and detected that only a few explicitly state what type of contribution they accept in this format (systematic review, empirical work etc), while the majority none-explicitly indicate that they accept experimental work only (see Supplementary Table 1). Thus, we call journals to be more explicit about the type of research they accept as registered reports.

Funders can further support registered reports by providing dedicated funding for either publication of registered reports, or full research project that aims for publication as a registered report. For example, Cancer Research UK and Templeton World have a grant program to support research that will be published as a registered report (https://www.cancerresearchuk.org/funding-for-researchers/how-we-deliver-research/positive-research-culture/registered-reports, https://www.templetonworldcharity.org/projects-database/0593).

Dedicated teams of experts who would support researchers in registering their study and also who would check/review pre-registered studies for any design issues would increase the quality of studies before they are conducted, and potentially eliminate almost 70% of research waste. These teams could be established at the funder's level (all funded work is checked), institution level (all research from an institution is checked), the national level (e.g. institutes that promote rigour and quality of research), or at a disciplinary (international or national) level. In some cases, pre-registrations could also be opened to the stakeholders (e.g. farmers that are affected by a proposed intervention) to provide input. This kind of input should be done quickly so the start of the study is not postponed. Finally, dedicated teams could also follow the study after it starts and help address any issues that (as often happens) arise down the line.

Funders, publishers, and institutions could also introduce pre-registration through changes in policies, as done by many in medicine. For example, introducing the International Committee of Medical Journal Editors (ICMJE) trial registration policy led to the implementation of laws and policies in the United States and internationally that expanded mandatory prospective trial registration[58,59]. However, before mandating registration, policymakers first need to build a good support system (incentives, infrastructure etc.). Incentives could involve giving pre-registration badges (https://osf.io/tvyxz/wiki/1.%20View%20the%20Badges/) or providing higher weight to the value of pre-registered studies compared to those that were not pre-registered when making decisions about promotions, grants acquisition and similar. Further, we note that not all research will be equally easy or even possible to register (e.g. fully exploratory research). Thus, any initiatives that aim to increase registration should be well planned not to discriminate against such research. Funders, publishers, and research institutions should also establish a system to check whether policies are followed. For example, among 14 medical research funders in Europe that require prospective trial registration, only some monitor whether trials are indeed registered (9 funders) or whether results are made public (8 funders)[29]. Text mining and other AI-driven solutions could be of great benefit here. For instance, PLOS and DataSeer have developed such a tool to monitor Open Science Indicators in PLOS journals[60].

Finally, apart from funding set-up of registration infrastructures and templates, funders should fund meta-research projects on pre-registration and registered reports in ecology. These projects could for example systematically evaluate the effectiveness of policies, mandates, and incentives in increasing the quantity and quality of registration in ecology. They could also study the effectiveness of registration in decreasing research waste and increasing the robustness of ecological studies.

Potential issues

Researchers' have concerns regarding pre-registration and registered reports (e.g.[16,49,52]). These for example include potential limitations on exploratory research, concerns about whether the approach will stifle innovation and creativity, and time and effort required to complete the pre-registration process. These valid concerns could be addressed by set registration standards (e.g. what to register), better support for registration, and an appropriate set of incentives, all of which would lead to a change in research culture where registration would be a norm, rather than an exception.

Developing and maintaining an efficient registration system will be costly. While data on the costs and benefits of registration are yet to be properly collected and evaluated, we trust that the benefits should outweigh the costs. For example, the 2007 budget for clinicaltrials.gov was $3 million[61] (Kimmelman & Anderson, 2012), yet, estimated US$170 billion invested in medical research is wasted annually[62]. Other issues that require further discussion include filed-appropriate preregistration procedure(s) and content, uniformity of registrations (e.g. does the registering authority have equal criteria for all types of studies), and procedures to ensure timely review of pre-registration and registered reports.

Study registration is a vital component in improving the transparency and findability of ongoing and completed research, but is neither a "magic bullet" nor a quick solution to increasing research quality and decreasing research waste. In the decades since Simes[63] argued the case for universal registration of clinical trials in medicine, the needed infrastructure and processes have gradually been put in place. However, progress towards all trials being registered has been slow, and led to the AllTrials campaign which launched in 2013 to have "All trials registered; all results reported" (https://www.alltrials.net/). Many ethics committees, funders, and publishers now require trial registration and clearly that would not have been possible without the infrastructure and culture change. However, policies do not guarantee that clinical trials will be prospectively registered[64,65], and registration does not necessarily translate into publications free of selective reporting[36,39,65] (see also references in Supplementary Table 3). While registration of clinical trials is getting closer to 100%, we are still a way from all results being reported. For decades this lingered at around 50%[24], but recent analyses show improvement. For example, of 1,970 trial registrations on ANZCTR, 541 (27%) remained unpublished 10 to 14 years later, and the proportion of trials published decreased by 7% from 2007 to 2011[66]. It should be noted that trials represent only a small fraction of health and medical research, and much of that remains unregistered. The lessons from clinical trials could and should be applied more widely in medicine, and in other disciplines.

Registration also cannot completely eliminate publication bias[67,68] nor questionable research practices. However, registration will make the underlying process (planned data collection and

analyses, and any deviation from these) transparent, and thus aid better interpretation and evaluation of study results[15].

Constructive dialog towards change – how to start

Above, we have discussed long-term actions that journals, funders, and research institutes could do to support registration. We have also highlighted some potential issues that need further discussion. As such, this paper is aimed at setting a fertile ground for an open dialog about the role of registration in ecology, and the best ways to support it.

To continue this discussion and dialog, in the near future, we hope to see journal editorials or even series that cover topics of registration, including meta-studies that evaluate what works and what does not, and why (e.g. what policies work, how well, does registration improve study quality, what are the costs and benefits of registration). We also hope to see increased funding for projects to improve registration and evaluate its effects (e.g. does pre-registration really reduces waste). Journals and funders should aim to start forums on improving research quality (including pre-registration). Finally, publishers, funders, and research institutions should work together with the research community that they aim to support. For example, in Box 1. we provide an example of the collaborative development for two reporting checklists (CONSORT and SPIRIT) that 'improved clinical trial design, conduct and reporting'[69].

Box 1. Good practice example

Two guidelines developed by the clinical trial research community greatly improved reporting[69]. The first, Consolidated Standards of Reporting Trials (CONSORT), focuses on improving the reporting of the results of clinical trials[70]. The second, Recommendations for Interventional Trials (SPIRIT) guidelines help with reporting clinical trial protocols[71]. Both guidelines are formatted as a checklist, facilitating complete reporting trial results, and trial protocols.

The CONSORT guidelines were introduced in the mid-1990s by researchers, statisticians, biomedical editors and clinical trialists who recognized the need for improved reporting standards in clinical trials[72]. Their efforts were supported by multiple journals and editors who endorsed the guidelines and made adherence to them a requirement for publishing clinical trial results[69,70,73]. The promotion and requirement of CONSORT is also extended to funders, such as German Research Foundation, the French National Institute of Health & Medical Research and UK's Medical Research Council[29]. The SPIRIT guidelines were formally published in 2013, following and initiative that began in 2007 and included 115 stakeholders (e.g. trial investigators, health care professionals, journal editors, representatives from research ethics community, industry and non-industry funders)[71]. Detailed protocol for developing SPIRIT guidelines is described in Chan et al. 2013[71] and it was based on: '2 systematic reviews, a formal Delphi consensus process, 2 face-to-face consensus meetings, and pilot-testing'. Both CONSORT and SPIRIT underwent (and continue to undergo) extensive consultation, consensus-building, and feedback from different stakeholders, leading to revisions that refine and enhance guidelines[69].

The impact of CONSORT and SPIRIT guidelines has been widely recognized and translated into 13 and 7 languages, respectively[69]. CONSORT even rose to one of the "top health research milestones of the twentieth century, according to the Patient-Centered Outcomes

Research Institute, and is among the top 1% of all research articles by article-level metrics, as tracked by Scopus"[69]. The wide application of both CONSORT and SPIRIT guidelines likely stems from design of the checklist, which can be applied across different medical disciplines that perform clinical trials and can be extended to requirements of the specific field if needed[74]. Additionally, developing guidelines is based on agreement between various stakeholders and has a user-testing stage that enables informing the guidelines[74].

Ecology can learn from these examples of good practices. For instance, when developing minimal registration criteria and registration templates, we should aim for generally applicable guidelines that can be extended to suit diverse ecological fields. Furthermore, involving different stakeholders (e.g. funders, publishers, and research institutes) who can offer registration incentives enables researchers to test criteria and templates, thereby facilitating the establishment of registration standards that are easy to follow.

In summary, we hope that more than 80% of wasted ecological research provides a strong incentive for funders, publishers, and research institutions to start and continue supporting pre-registration in ecology. While we focus on pre-registration in this Perspective, we want to emphasise that it is essential that funders, publishers, and research institutions support researchers in adopting other open science practices and principles as these are also essential to increase the quality of research. A nice overview of these can be found in[75].

Learning from solutions for registration in other fields (notably medicine) we also propose some specific aspects that should be considered for ecological research. These primarily include establishing ecology-specific infrastructure to enable registration and promote registered reports, accompanied by the development of tools and templates for minimal registration requirements or software and data management. We also call for the provision of support through i) expert teams that would help with registration, check pre-registered studies, and monitor study after it starts, and ii) education and training for researchers, students, and support staff. Furthermore, we advocate for a 'reward and require' system that first, provides incentives to encourage registration practices, and then mandates it. Finally, we call for an evaluation of our claims via meta-research approaches to assess the effectiveness of registration and guide future advancements.

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Author contributions

Conceptualization: all authors; Data curation: M.P. and A.C.; Formal analysis: M.P. and A.C.; Funding acquisition: T.K.; Investigation: M.P. and A.C.; Methodology: A.C.; Supervision: A.C.; Validation: A.C., T.K, S.N., P.G.; Visualization: M.P. and A.C.; Writing - original draft: A.C. Writing - review & editing: all authors.

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Conflict of interest

Authors declare no conflict of interest.

Note: A.C., S.N. and M.P. are officers at the Society for Open, Reliable, and Transparent Ecology and Evolutionary biology (SORTEE).

Supplementary Methods to Purgar et al. (2023): Supporting study registration to reduce research waste

Journals offering registered reports

We used OSF list of journals that offer Registered Reports, and extracted those that publish ecological and evolutionary biology research (25 journals). The list is kept by the OSF here Registered Reports (cos.io) (under tab 'Participating journals') and we accessed the list on the 20th of May 2023. We added one additional journal to the list, Nature Ecology and Evolution, as this journal just recently adopted Registered Reports, and was not entered in the OSF table. We have checked each journal additionally to double check if they do offer registered reports, number of registered reports (Stage 1 or 2) that were published prior to 10th of July 2023, to examine their instructions to authors, and to check whether they clearly state what type of registered reports they support (e.g. experimental research, meta-analyses etc.). Table with information extracted from the journals is presented in Table S4 bellow. We could not detect any reference to registered reports in one of the journals (Frontiers in Plant Science). Further, one of the journals (BMC Ecology) listed at the OSF list has merged with another journal (BMC Ecology and Evolution). While BMC Ecology had registered reports, we could not determine whether BMC Ecology and Evolution specifically supports this type of contribution. We have thus emailed both journals and they confirmed they do not support registered reports. Our final list of 24 journals for which we could confirm the acceptance of registered reports can be accessed at Supplementary Table 1.

Table S4. Information extracted from ecological journals that accept registered reports.

Extracted information	**Description [values]**
Journal	Title of the journal [free text]
Link to Instructions for Authors	Web link to instructions for authors [free text]
Year of adoption	Year in which registered reports were introduced to specific journal [free text]
Introduced as	Information on how registered reports policy was introduced, e.g. editorial, and a link to introduction ['announcement', 'editorial', 'blog post' and free text] NA denotes cases where we could not find the information on RR introduction policy.
Number of published registered reports	Denotes findable number of published registered reports. If a journal offered a search tool that enabled targeting registered reports, we noted the number of observed published registered reports (e.g. 0, 1, 2 etc.). If, however, we could not search by article type because

	there was no such option offered on the journal website, we denoted these with 'NA'.
Explicitly states supported type of studies (e.g. experimental, observational, replications) for RR	Denotes which type of study is supported as registered report, e.g. experimental, observational, replications, meta-analyses etc. ['yes' or 'no' plus free text copy-pasted from journal policy]
Note	Additional relevant information [free text]

Exploratory survey

We conducted an exploratory survey to find meta-studies that evaluated the effect of registration (pre-registration and registered reports) on any aspect of study's methodological or reporting quality, and features of study results (effect size, statistical significance etc.). The aim of this survey was a quick scan of the existing literature in order to provide some evidence to support (or not) the claims provided in the Perspective, and not a systematic and comprehensive search for all the literature published on the topic. Thus, the survey was not registered and can be used as a starting point for a comprehensive systematic review.

We searched for meta-studies that compared pre-registered studies or registered reports with standard published literature. We have also aimed to detect studies that compared results registered in the registry with those reported in the related publication.

We conducted a search of published literature on June 13th, 2023, using the Web of Science (WoS) Core Collection, accessed through Ruder Boskovic Institute, Zagreb, Croatia. The search string was defined based on keywords, Boolean, and adjacency operators, and was searched for in All Fields (Field Tag "ALL"). The search string was as follows:

((ALL=(Register* OR registrat* OR RR OR registry)) AND ALL=("standard literature" OR "Standard publishing" OR "Published literature" OR "Published articles" "Published work" OR "Published reports" OR "published trials" OR "published studies" OR "published research" OR "unregistered studies" OR "unregistered trials" OR "non registered studies" OR "not registered studies" OR "non registered trials" OR "not registered trials")) AND ALL=("research quality" OR "publication bias" OR "questionable research practices" OR "reporting quality" OR "quality of reporting" OR "transparency" OR "positive study findings" OR "positive results" OR "effect estimates" OR "effect size estimates" OR "treatment effects" OR "positive study findings" OR "statistically significant" OR "selective reporting" OR "result reporting" OR transparent OR reproducible).

We supplemented this with 11 meta-studies already known to us. The WoS search led to 800 results which were exported to Ryyan. Title and abstract screening were done by AC and MP. 50 articles were double-screened with 100% agreement rate. Overall, 69 articles passed to full-text screening out of which 25 were included in the final sample. As we were interested in the potential effects registration has on study design, publication bias, and reporting we included all meta-studies that compared i) registered reports and non-registered reports (N=5),

ii) registered reports and pre-registered studies (N=1), and iii) pre-registered studies and non-pre-registered studies (N=21). Note that this category (ii) was deemed relevant post-hoc and not prior to our search. We also included studies that compared discrepancies between the results reported in the pre-registration and its resulting publication (N=12). The overall process is presented in the PRISMA diagram, Fig. S1.

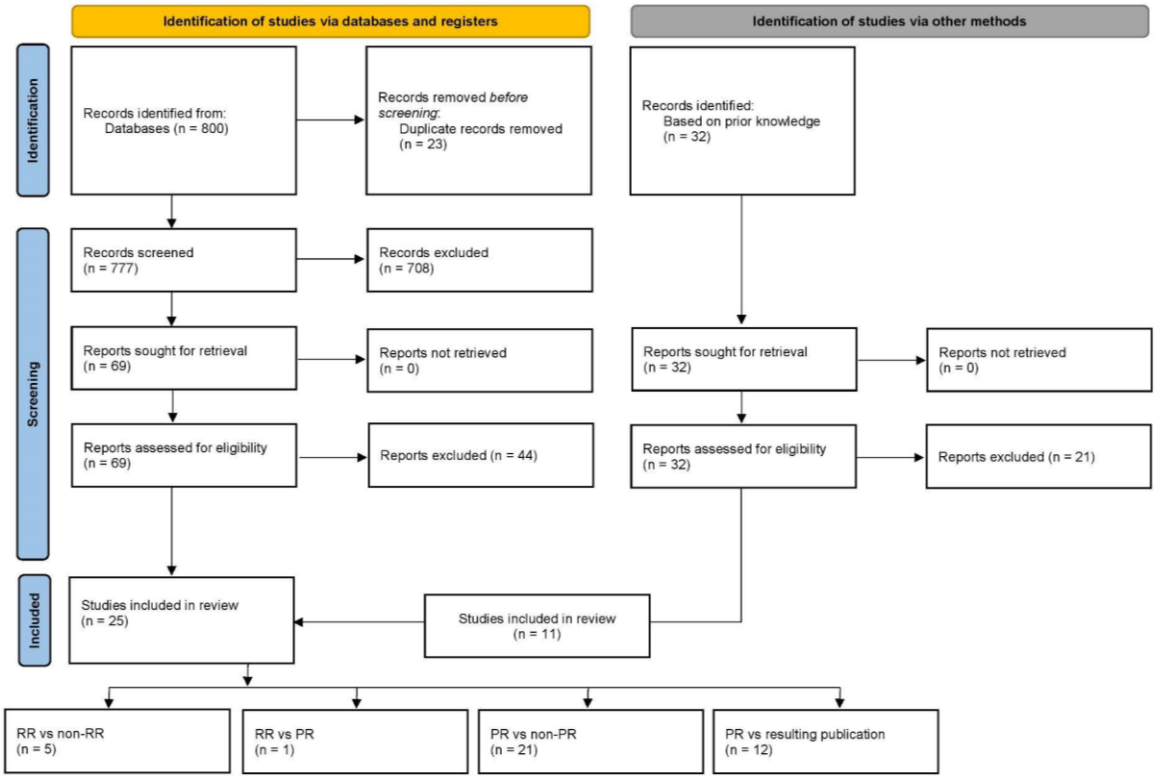

Figure S1. PRISMA flow chart of the exploratory survey and screening process. Generated with https://estech.shinyapps.io/prisma_flowdiagram/. This process resulted in 36 relevant studies, that compared i) registered reports and non-registered reports (RR vs non-RR), ii) registered reports and pre-registered studies (RR vs PR), and iii) pre-registered studies and non-pre-registered studies (PR vs non-PR), (iv) results reported in the pre-registration and its resulting publication (PR vs resulting publication). Note that some papers had effect estimates for several categories and we had overlaps (e.g. RR vs PR and PR vs non-PR).

Data extraction from the final list of meta-studies (25 from WoS search, and 11 from prior knowledge) was done by AC and MP, and the detailed extracted data are presented in Supplementary Tables 2 and 3. Information collected from each study is given in Table S5.

Table S5. Information extracted from papers

Extracted information	**Description [values]**
Paper	Title of the paper (meta-study) [free text]
DOI	Digital Object Identifier [free text]
Field	Study field [medicine, psychology, psychology - parapsychology]

PR or RR	Denotes whether the study focused on pre-registration (PR) or registered reports (RR) [PR, RR]
Compared	What was compared to what [PR (prospective vs retrospective) vs non-PR,PR (prospective) vs non-PR, PR prospective vs retrospective, PR vs non-PR, RR vs non-RR, RR vs non-RR (but only replication studies), PR vs RR, PR vs resulting published article, published vs not pre-registrations]
Effect on	What part of study feature has the meta-study examined [design, reporting, results, publication bias]
Effect on detailed	Detailed description of the effect examined [sample size, risk of bias, spin, result direction (in favour or not), effect size, quality score,quality score based on PEDro, statistical significance, methodological reporting, reporting important methodological details associated with risk of bias (and likely lower RoB), reporting on methodological aspects, transparent reporting (and likely better design), quality score, result direction (hypotnesis supported or not),reporting or not on serious adverse effects, reporting of all key elements, according to three experts, for the flow of participants, efficacy results, adverse events, and serious adverse events]
Method	General methodology of the study [free text, copy-pasted from the meta-study]
Results	Results, as presented in paper [free text, copy-pasted from the meta-study]
Other info	Other potentially relevant or interesting information [free text, copy-pasted from the meta-study]
From	Denotes how study was identified: via literature review or from our previous knowledge [LitRew, Previous]