**The Tao of Open Science for Ecology**

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**Abstract**

The field of ecology is poised to take advantage of emerging technologies that facilitate the gathering, analyzing, and sharing of data, methods, and results. The concept of transparency at all stages of the research process, coupled with free and open access to data, code, and papers, constitutes "open science". Despite the many benefits of an open approach to science, a number of barriers to entry exist that may prevent researchers from embracing openness in their own work. Here we describe several key shifts in mindset that underpin the transition to more open science. These shifts in mindset include thinking about data stewardship rather than data ownership, embracing transparency throughout the data life-cycle, and accepting critique in public. Though foreign and perhaps frightening at first, these changes in thinking stand to benefit the field of ecology by fostering collegiality and broadening access to data and findings. We present an overview of tools and best practices that can enable these shifts in mindset at each stage of the research process, including tools to support data management planning and reproducible analyses, strategies for soliciting constructive feedback throughout the research process, and methods of broadening access to final research products.

**Keywords:** data management; ecology; open access; open science; reproducible research

**Introduction**

Ecology stands at the threshold of a potentially profound change. The combination of ever-increasing computational power, coupled with advances in Internet technologies and tools, is catalyzing new ways of pursuing ecological investigations. These emerging approaches facilitate greater communication, cooperation, collaboration, and sharing, not only of results, but also of data, analytical and modeling code, and potentially even fully documented workflows of the processes---warts and all---that lead to scientific insights. This vision of free and unfettered access to all stages of the scientific endeavor has been called "open science" (Nielsen 2011). As an integrative and highly multidisciplinary field, ecology particularly stands to benefit from this open science revolution, and many ecologists have expressed interest in enhancing the openness of ecology. To date, such conversations among ecologists have largely occurred online (e.g., discussed in Darling et al 2013); thus it seems timely to present an introduction of open science for ecologists who may or may not currently be active in social media where the discussion is evolving. We give an overview of the rise of open science, the changes in mindset that open science requires, and the digital tools that can enable ecologists to put the open science mindset into practice.

The exchange of scientific information was first institutionalized in the 1660s with the establishment of the Philosophical Transactions of the Royal Society of London and the Journal des Sçavans, the first scientific journals (Beaver and Rosen 1978).  While these journals provided platforms for scientists to share their results and ideas, they were largely accessible only to elites---those who could afford a subscription themselves, or those who belonged to an institution that held copies (Nielsen 2011).  Scientists published in these journals to establish precedence of discovery; the notion of collaboration among scientists does not seem to have taken hold until the 1800s (Beaver and Rosen 1978).

The scientific world looks very different now. Advances in computing accelerated not only individual scientists’ discoveries but also their collaborative potential (Box 1). Modern scientists constitute a new invisible college with global reach, its philosophical transactions enabled by the Internet (Wagner 2008).  Collaboration has become the predominant norm for high-impact research (Wuchty et al 2007). Technological developments also have enabled the capture of a previously unimaginable volume of data and metadata at ever increasing rates (Reichman et al 2011, Dietze, M.C., D. LeBauer, R. Kooper. 2013), and the deployment of greater computational power to run models and analyze data. Traditional paper notebooks cannot meet the challenges of increased accumulation, sharing, and recombination of ideas, research logs, data sets and analyses (Strasser and Hampton 2012). Nor can a non-networked computer.  The tools and approaches that together constitute open science can help ecologists to meet these challenges, by amplifying opportunities for collaboration and demanding consistent machine-readable documentation necessary for rapid reproducibility in complex projects.

While interest in this new paradigm is on the rise (Fig. 1), it must be acknowledged that both technical and sociocultural obstacles impede adoption for some ecologists. For example, precedence, attribution, investment, and payoff are high-stakes issues for professional scientists (Hackett 2005). Adopting open practices means ceding some control of these issues, and devoting precious time to learning new modes of research and communication in a seemingly foreign language (Box 2). Yet hewing to traditional practices carries its own risks for the individual investigators. Errors and oversights can persist far longer when experimental design and data analysis are held in private; weeks and months can be wasted in chasing reproduction of results because methods are documented only as fully as a journal word count permits; labs can become isolated, their advancement slowed, for lack of substantive interaction with others. Open science can help to mitigate these risks, to the immediate benefit of the individual practitioner, as she builds an active community around her.

Moreover, open science promises many longer term benefits to the scientific community. The adoption of standard best practices and cultural norms for public archiving of data and code will speed discovery and promote fairness in attribution. The use of open-source tools and open-access data and journals will help to further democratize science, diversifying perspectives and knowledge by promoting broader access for scientists in developing countries and at under-resourced institutions, and fostering citizen science which is already a major source of data in some ecological sub-disciplines (Cooper 2014).

Here, we discuss the changes in mindset and the tools that can help interested ecologists move toward practicing open science themselves, facilitate its practice by their students and other colleagues, or both.

**Changes in mindset**

*Data stewardship, not data ownership*

Traditional views on data ownership hold that data are proprietary products of the researcher (Sieber 1989). By definition, this data ownership mindset limits the potential for data sharing as a given researcher can restrict the conditions and circumstances by which their data are disseminated. These views have persisted for a variety of reasons (Sieber 1989, Hampton et al 2013, Lindenmeyer and Likens 2013) and ecologists historically have treated data as proprietary whether or not the data collection has been funded by taxpayers and might reasonably be considered public property (Obama 2013).

Under the principles of open science, data are generated with the expectation of unfettered public dissemination. This fundamental shift in thinking from "I own the data" to "I collect and share the data on behalf of the scientific community" is essential to the transparency and reproducibility of the open science framework. When data are available, discoverable, and well-described, scientists can avoid “reinventing the wheel” and instead build directly on those products to innovate. For example, authors’ reluctance to submit null results for publication leads to a "file-drawer" effect that can not only systematically bias the published literature (Iyengar and Greenhouse 1988, Franco et al. 2014) but also allows independent scientists to go repeatedly down the same blind alleys. Structures to store, share, and integrate data contribute to avoiding such waste of scientific resources. Beyond this greater efficiency, data sharing also contributes to the production of entirely new scientific products that were not envisioned at the time data were collected (Carpenter et al 2009).

Norms have yet to be established in ecology for how soon after collection data should be shared in order to promote openness and a healthy scientific culture, and a range of data sharing practices is currently employed by scientists who are philosophically aligned with open science (Figure 2). A full embrace of open science data would mean sharing data instantaneously, or upon completion of initial quality assurance checks or other pre-processing (e.g., NEON; ref). In other cases, researchers have made an argument for a constrained period of exclusive access by researchers directly involved in data collection (e.g. Sloan Digital Sky Survey; <http://www.sdss.org/>). In any case, it is increasingly recognized in the requirements of funding agencies that full data sharing in established repositories should begin no later than the publication of results.

*Transparency throughout the data life-cycle*

Scientists publish their methodology with reproducibility by others in mind, but have traditionally had to judge which details were important to transmit within limitations imposed by print journals. The availability of online supplementary methods sections gives scientists scope to detail their methods more fully, and a broader suite of online tools now creates opportunity to share the code, data, and detailed decision making. Taking advantage of these opportunities to make tacit knowledge explicit to others is a crucial part of performing reproducible research (Collins 2001, Ellison 2010), and has the substantial additional benefit of making such knowledge explicit to oneself, with the potential to shed light on untested assumptions and unidentified confounding effects.

Workflow tools (Table 1) now make it possible for scientists to make every stage of the research process transparent, from sharing the detailed rationale for an approach to publishing the data and code that generated analyses and figures.  Detailed sharing of methods and code improves clarity; personal communications regarding methods crucially improves trust (Collins 2001), and social media permit these communications too to happen in the open.  Openness throughout the data life-cycle also provides the scientist with the opportunity to receive extensive feedback from the rest of the scientific community and can improve the quality of that feedback (Byrnes et al 2014).  Whereas formal peer review provides feedback only at the project’s proposal phase (for those seeking grant support) and conclusion, open science provides an avenue for scientists to receive feedback at key junctures, e.g., before experiments are performed.

Additionally, transparency encourages researchers to converge on standard structures for data and code archiving (Table 1).  Such convergence is particularly important for interdisciplinary science, in which the fragmentation of resources and practices along disciplinary boundaries can substantially hinder research.  Common standards and a shared, searchable infrastructure help make data sets not merely open but also discoverable, improving their reach and impact and helping scientists identify potential new collaborators.

Having said all this, scientists need not fear that open science is only for the exhibitionists among us; we recognize that there are many points in the scientific process when deep, sometimes solitary reflection is invigorating and productive.

*Acceptance of critique*

Failure is recognized as a normal and necessary part of the scientific process, and yet academic science is structured to reward only being right in public (Merton 1957), creating tension in practicing open science. The more open our science, the greater the chance that our mistakes as well as our insights will be publicly available. This prospect can be frightening to contemplate; one study of physicists found that those practicing secrecy prior to publication often did so to avoid the risk of looking foolish (Gaston 1971).  We suggest that embracing this tension gives us the opportunity to be better and more productive scientists. The only way to protect our ideas and methods from criticism indefinitely is to refrain from publication, hardly a desirable outcome.  Even delaying exposure until peer review manages only to limit the possible range of feedback to being told what could have been done better. By contrast, adopting open practices throughout the scientific endeavor makes it possible to receive and incorporate critiques before our research products are complete. That is, by risking the possibility of being briefly wrong in public, we improve our chances of being lastingly, usefully right.

**Tools and best practices to enable shifts in mindset and practice**

An open science mindset affects the entire scientific process, carrying responsibilities and offering benefits at each stage along the way (Figure 2). If we are committed to data stewardship, planning an experiment entails not only thinking through the physical manipulations involved but also working out how to capture and share the data and metadata that will enable others to effectively re-use that information.  The open-source DMPTool (Table 1) offers guidance to scientists creating data management plans---now often a prerequisite for funding---and helps scientists find institutional resources for implementation.  At the same time, ready access to data sets collected by other scientists can help focus our questions, by identifying gaps and opportunities, and improve our ability to answer them (e.g., by allowing us to estimate and plan for experimental uncertainties). Once data has been collected, the open scientist prepares the data set for use by others and documents its provenance (e.g., with tools from rOpenSci), then deposits it in a community-endorsed repository (e.g., Knowledge Network for Biocomplexity, Dryad).  This process ensures that the data will remain usable and accessible for years to come, allowing our work to be integrated into the body of knowledge and ensuring that, when we return to a project after a period away, we can pick up where we left off.

If we are committed to transparency, we document and share as much information about the process as feasible.  Electronic lab notebooks (e.g., using IPython notebooks) help track and share the reasoning behind our experimental and analytical decisions, as well as the final protocol and any deviations, and can be linked to the resulting data files to keep research organized.  Adhering to the discipline of consistently, carefully, and thoroughly documenting the research process is an exercise in critical thinking, a constant reminder to check our assumptions and clarify our thinking.  During data analysis, reproducible, script-based methods (e.g., in R or Python) can be used for every step from importing raw, uncleaned data to analysis and production of figures and final manuscripts (e.g., FitzJohn et al 2014). Such tools are essentially self-documenting along the way, providing a complete record of data manipulations that is much more difficult to generate for point-and-click analyses in a graphical user interface (GUI).  While errors can be made in both scripted and GUI-based analyses, the existence of a record makes errors in the former far easier to detect and correct, protecting the integrity of the analysis. Tools such as markdown and knitr facilitate integration of data analysis into manuscript production, making it easier to keep figures and reported results current as an analysis is refined.  All of these steps are undertaken with an eye to making our work reproducible and open to others, but all offer the immediate benefit of making our work reproducible and open to ourselves. Many of the tools mentioned in Table 1 have proprietary analogs (e.g. as SAS is to R), and afford many similar advantages, but exclusive use of open-source, free software maximizes access by other researchers.

If we are committed to openness to critique, we make documentation public as early as possible in the development of a project (Figure 2).  Experiments can be discussed using the features of publicly available electronic lab notebooks or on social media (Gewin 2013, Darling et al 2013); code can be examined and potentially improved in public code repositories (e.g. Github); figures and movies can be opened for comment on public websites (e.g. Figshare). In all cases, the open scientist seeks repositories with stable identifiers (e.g., stable URLs and DOIs) rather than relying more than necessary on one’s own servers. All of these tools give us access to a research group far bigger than a single lab, helping experimental designs to be improved and stimulating discussion of worthwhile new directions, connections, and approaches.  As a project draws to a close, preprints can be posted for comment from a broader audience than a journal's handful of peer reviewers; preprints also improve a project's visibility and, with the addition of a date stamp, establish precedence (Desjardins-Proulx et al 2013).  Publishing final papers in open-access journals ("gold" open access) or self-archiving manuscripts ("green" open access) makes the final products available to a wide audience, including the taxpayers who funded the research.

Version control (e.g., Git, SVN) at every stage is a highly recommended best practice (Noble 2009, Wilson et al 2014), supporting every aspect of the open science mindset. Version control systems, accessible through user-friendly tools like GitHub, allow scientists to retain snapshots of previous analyses for future reference, collaborate easily and track contributions, record ideas, and safeguard against the loss of code and data (Ram 2013), thus preserving the long-term integrity of the project even as collaborations form and shift.

**Conclusions**

Online tools make possible a future in which not only scientific practice but also scientific culture are transformed by openness (Hey et al 2009, Nielsen 2011).  Fully open science would be apparent from end to end of discovery, from the sharing of nascent ideas that can be improved upon by active discussion, to the instantaneous upload of data at the moment of capture, through the full development of "living papers" in an open forum in which the details of analysis and reasoning are completely transparent.  Subsequent generations of ecologists will build their work on what we leave.  If instead of paywalled journal archives we leave them open-access repositories of data, code, and papers, they will be far better equipped to push new frontiers in science and create solutions to pressing societal problems.

Very real technological and cultural hurdles still stand between us and this future:  investigators must be willing to invest time in learning the tools that facilitate open science, and in re-learning them as the tools evolve, while the scientific community must collectively establish new norms for collegiality and reproducibility in the digital age. Nevertheless, we can all move our research toward this future by adopting the aspects of open science that are currently feasible for our labs (e.g., publishing open-access articles; sharing all data and code used in publications) and by supporting our students and junior colleagues in developing the skills that will best prepare them for the responsibilities, opportunities, and rewards of practicing ecology in an open environment.

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**Table 1:** A wide range of tools is available to support open science at each stage of the research life-cycle.

|  |  |  |
| --- | --- | --- |
| **Concept** | **Name of Tool or Service** | **Tool Description** |
| ***Ideas & communication*** |  |  |
| Open discussion | Twitter | Twitter allows users to write, share, and respond to short 140 character messages. An ever-increasing community of scientists uses Twitter to share ideas about research (Darling et al. 2013) |
|  | Blogs | Blogs can be hosted on university websites, personal servers or blogging sites (e.g. wordpress.com). Blogs offer an informal means of discussing ideas, results, published literature etc. |
|  | Open lab notebook | Open lab notebooks apply the concept of blogging to day-to-day research work: research notes and data are published online as they are accumulated. |
|  | GitHub comments | GitHub comments allow others to review code and offer comments on particular sections. |
| ***Hypotheses/ Design*** |  |  |
|  | Data Management Planning Tool | The Data Management Planning Tool enables researchers to easily create, manage and share data management plans that meet the requirements of a broad array of funding agencies and institutions. |
| ***Data collection*** |  |  |
| Support of the Data Life-cycle | Data repositories: KNB, DataONE, Dryad | Data repositories make data available to future researchers and allow the reproducibility of research; they are a cornerstone of open science. |
|  | Open Office | Open Office is a comprehensive office tool suite that supports word processing, spreadsheets, graphics, presentations, drawing, and creating and maintaining databases. |
|  | MySQL | mySQL is a popular and widely used open-source relational database management system (RDBMS) based on Structured Query Language (SQL). |
|  | Open Refine | OpenRefine is a powerful tool for exploring and cleaning messy data, transforming it from one format into another, and link and extending data with web services and databases. |
|  | Morpho | Morpho is a program that can be used to enter metadata, which are stored in a file that conforms to the Ecological Metadata Language (EML) specification. |
| ***Analyze and Visualize*** |  |  |
| Reproducibility | R | R is a widely used statistical programming language that is commonly used for analyzing and visualizing data |
|  | RStudio | RStudio is a Integrated Development Environment (IDE) for R |
|  | Python | Python is a widely used high level programming language that is commonly used for managing and manipulating data. |
|  | Pycharm | Pycharm is one of several IDEs available for python |
| Version control | Git and GitHub | Git is a piece of software that allows you to create 'versions' of your code, text, and project files as you work on them. GitHub is a website that allows this to be done collaboratively, with social and discussion features built in. |
| Free alternatives for GIS | GRASS | GRASS (Geographic Resources Analysis Support System), is a Geographic Information System (GIS) software toolset used for geospatial data management, analysis, and visualization, as well as image processing and spatial modeling. |
|  | QGIS | QGIS is a desktop GIS application that supports geospatial data viewing, editing, and analysis. |
| Workflow tools | Kepler | Kepler is a scientific workflow package that allows researchers to create, execute, and share analytical models. |
|  | VisTrails | VisTrails is a scientific workflow and provenance management system that supports data exploration and visualization. |
| Reproducible documents | Sweave | Sweave was originally a way to integrate S and LaTeX, but now also works with R. |
|  | IPython notebook / Project Jupyter | The IPython notebook (now renamed Project Jupyter and focusing on R and Julia in addition to python) is a tool for interactively analyzing and processing data in the browser using blocks of code. |
|  | markdown | Markdown is a simple markup syntax for adding formatting to documents. It allows correctly formatted scientific documents to be written in plain text. |
|  | pandoc | Pandoc allows conversion between many document types, including LaTeX, markdown, PDF, and Word (.docx) |
|  | knitr | knitr is a newer package that allows the integration of a whole number of different scripting languages in a single document |
|  | Rmarkdown | Rmarkdown is an authoring format which combines markdown with the syntax of both knitr and pandoc |
| ***Presenting preliminary results*** |  |  |
| Share results and get feedback | Figshare | An online repository for all types of research products (data, posters, slides, etc) that assigns each a citable DOI |
|  | Slideshare | An online clearinghouse for presentation slides of all types |
|  | Speakerdeck | An online site for sharing PDF presentations (run by GitHub) |
| ***Writing*** |  |  |
| Enhance collaboration | Google Docs | Online collaborative writing, spreadsheet, and presentations tools |
|  | Etherpad | Online, open source, collaborative writing tool |
|  | ShareLateX | Online collaborative writing tool (like Google docs) focused on LaTeX |
|  | WriteLaTeX | Online collaborative writing tool (like Google docs) focused on LaTeX |
|  | Authorea | Online collaborative writing tool (like Google docs) focused on LaTeX |
| Citing research | Zotero | Zotero is a free and open source extension to the Firefox browser (and now a standalone app) that can help with literature management and citation |
|  | Mendeley | Mendeley is a free reference manager and social network for researchers. |
| ***Preprint*** |  |  |
| Share results and get feedback | bioRXiv | bioRXiv, run by Cold Spring Harbor, is a relatively new preprint server that focuses more exclusively on biology |
|  | arXiv | arXiv is one of the original preprint server on the web. Run by Cornell, it is mainly focused on math, physics, and computer science, although it has been used by quantitative biologists as well. |
|  | PeerJ Preprints | PeerJ Preprints is a preprint server run by the open-access online-only journal PeerJ |
| ***Pre-publication peer preview*** |  |  |
|  | Peerage of Science | Pre-publication formal peer review (and review of the reviews), which can then be sent on to participating journals |
|  | Axios Review | Pre-publication formal peer review and appraisal of a manuscript's fit with targetted journals; reviews can then be sent on to participating journals |
| ***Publish*** |  |  |
| Reduce barriers to access | DOI for code | Code can be given a DOI and cited in the literature. For example, a Github repository can be assinged a DOI via zenodo.org |
|  | DOI for data | Data uploaded to any of the numerous available online repositories will be assigned a DOI and is then citeable by other researchers using that dataset |
|  | "Green" open access | Open access whereby the author of a manuscript may post a pdf of their article to their own personal website |
|  | "Gold" open access | Open access where the authors pay a fee up-front (before publication) to allow their paper to be made open |
|  | Licences: CC-BY, CC-BY-NC etc | Licenses dicatate how a research product may be used by others - some have restrictions necessitating attribution, others mandate no commercial reuse, etc |
| ***Discussion of published literature and data*** |  |  |
| Finding published data | DataONE | DataONE is a federation of data repositories that supports easy discovery of and access to environmental and Earth science data, as well as various data management tools and educational resources. |
|  | re3data | re3data is a registry of digital repositories that enables researchers to discover public and institutional repositories where they may deposit and preserve their data. |
| Social networking for academics | ResearchGate | A social networking and question and answer site for academics |
|  | Academia.edu | Social netowrk for academics |
| Tracking research product impact | ORCID | Unique identifiers for individual researchers, which allows contributions to be tracked across many repositories, grant proposals, peer review sites, etc. |
|  | ImpactStory | ImpactStory can track almost all of the research contributions (data, code and papers) by individual researchers, and quantifies their impacts using open data sources (e.g. tweets, use in wikipedia articles, saves in Mendeley) |
|  | Altmetric | Provides metrics (tweets, blog posts, Mendeley saves, etc) of individual research objects |
| Informal discussion | Conference or hallway conversations, discussion groups | High efficiency but limited accessibility to outside researchers |
|  | Personal website/blog | Personal blogs can be a forum to discuss both one's own research as well as the research of other scientists |

**Box 1:**Technological advances driven by scientists

Every scientist now uses the Internet, but few are aware of how the Internet grew out of a highly collaborative and open process involving development of publicly available and commentable standard protocols which in turn spawned a vast, highly interoperable, international, communications network (<http://www.fcc.gov/openinternet>; Cerf 2002). First coined in the 1990s, the term "open source" encompasses not only compilers and applications but also protocols and specifications such as the domain name system (DNS) that allows pinpointing specific networked computers ("hosts") around the world, and HTTP/HTML specifications that provide the basis for the World Wide Web. The availability of open source software radically democratized and expanded participation in the Internet community in the late 1980s-early 1990s.

Members of the scientific research community were early recipients of these advantages, with the National Science Foundation supporting and nurturing growth of the Internet-based NSFNET from roughly 1985-1995 (National Science Foundation, 2007). In that era, it was scientists who were largely communicating through the Internet (gopher, email), transferring their data (FTP), and running analyses on remote servers (telnet, shell access, X11), often with privileged access to fast networks and accounts on powerful computational servers. Within this computer savvy community, "power users" leveraged the Internet most effectively via learning computational skills that were largely command-line based. The legendary, free GNU suite of software was standard issue for many computers joining the Internet in the late 1980s, and made that early generation of networked "scientific workstations" (from Sun, SGI, DEC, or NeXT) the sought-after systems of their day.

These early forays into powerful software helped birth the plethora of tools now available to the modern scientist.  Today, free, multi-platform, open source tools from the Linux Foundation (free operating system), the Apache Software Foundation (free Web server), the Mozilla Foundation (free Web, email, and other applications), the PostgreSQL Global Development Group (free enterprise database), the Python Software Foundation (free programming language), and the R Foundation for Statistical Computing (analysis and statistical language) are enabling researchers across the globe to dialog with one another via cutting edge communication, execute powerful data manipulation, and develop community-vetted modeling and analysis tools at little or no cost.

**Box 2:** “A glossary of open science for ecologists”

***citizen science:***enabling interested citizens to contribute their time, observations, and expertise such that these assist and inform the scientific research process; may be an aspect of ***crowd-sourcing***.

***code repository***: an accessible, central place where computer code is stored to facilitate the collection, manipulation, analysis, or display of data.

***crowd-sourcing***: leveraging the expertise and participation of many individuals, to provide more perspectives, critiques, data contributions, code contributions, etc. to advance a (scientific) process.

***data life-cycle***: the pathway researchers trace when documenting the natural world from idea generation through to making observations and drawing inference. It is popularly dissected into eight intergrading phases: Plan, Collect, Assure, Describe, Preserve, Discover, Integrate, Analyze (Michener et al 2012).

***data management***: the development and execution of architectures, policies, practices and procedures that properly manage the full ***data life-cycle*** needs of an enterprise (Mosley et al. 2009).

***data repository***: an accessible, central place where accumulated files containing collected information are permanently stored; typically these house multiple sets of databases and/or files.

***open access***: providing free and unrestricted access research products, especially journal articles and white papers-- to be read, downloaded, distributed, reanalyzed, or used for any other legal purpose, while affording authors control over the integrity of their work and the right to be acknowledged and cited. (adapted from the Budapest Open Access Initiative definition, Chan et al. 2002).

***open data***: data that can be freely used, reused, and redistributed without restrictions beyond a requirement for attribution and share-alike (Molloy 2011).

***open science***: Open Science is the idea that scientific knowledge, including data, observational and experimental design and methods, analytical and modeling code, as well as results and interpretations of these (e.g. reported in publications)-- are made freely accessible to anyone, and represented in transparent and reusable formats as early as practical in the discovery process by employing standards-based technology tools.  ***open science*** frequently encompasses all of ***open access***, ***open data*** and ***open source*** and, minimally, facilitates reproducibility of results.

***open source:*** computer code (software) that is available for free distribution and re-use, with source code unobscured, and explicit acknowledgement of the right to create derived works by modifying the code (Gacek and Arief 2004)

***preprint***: a draft version of a paper distributed (usually in an online repository such as arXiv) before a final, peer-reviewed journal or reporting agency has accepted or formally published the paper (Desjardins-Proulx et al, 2013).

***reproducibility, replicability, and repeatability***: while formal definitions of these terms vary widely and across disciplines, these all point to a hallmark of science, which is the ability to repeatedly generate or observe outcomes consistent with scientific understanding, based on explicit specification of theories, models, and methods, and their expected material realizations or outcomes.  This prescribes a need for sufficient access to data and analytical code to verify that a purported result is valid, as well as to examine these for errors and biases (Jasny et al 2011; Peng 2009; Stodden et al. 2013; Stodden 2009; but note Drummond 2009 and Casadevall and Fang 2010 use somewhat different definitions)

***transparency***: a scientific process is  described in enough detail that it is open to public scrutiny and examination; nothing is intentionally obscured by technology or process  

***version control***: a system that manages snapshots (and hence “revisions” or “versioning”) of code and data for a project (Wilson et al 2014). It facilitates detailed documentation to enable tracing any significant changes over a project’s lifetime.

**Figure 1.** Increase in “open science” in the literature

**Figure 2:** Three examples of possible open science workflows. In each workflow illustration, the *gray box* surrounds activities that are not openly accessible for researchers who are not directly involved. Activities outside these boxes are open and available, representing how the individual researcher is influenced by other scholars, or is able to communicate their research before and after publication. *White boxes* represent distinct research products available for reference for and feedback from other researchers.