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OSGEO, PERSISTENT IDENTIFIERS AND THE SHAPE OF THINGS TO COME

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ABSTRACT:

The Open Source Geospatial Foundation (OSGeo) is an international community, which maintains and develops a growing number of quality-assured open source geospatial software tools. OSGeo supports Open Science and the FAIR (Findable, Accessible, Interoperable, Reusable) principles. The open source software projects of OSGeo are drivers for innovation, but also benefit from technical advances made in other fields to foster FAIR. We report on the of adoption of persistent identifiers (PID) by OSGeo communities, which is accelerating and diversifying. Persistent referencing by PID was introduced to OSGeo for scientific video in 2014. Since 2017 it is being adopted by a growing number of OSGeo software projects to enable scientific citation of software repositories, individuals software releases and involved persons. This enables tangible scientific credit for OSGeo volunteer work and is expected to affect OSGeo workflows, such as the incubation and graduation process. For illustration, examples from the OSGeo projects GRASS GIS and actinia are provided.

1. INTRODUCTION

Since the 1980s, the Geosciences and Remote Sensing in particular have significantly evolved as part of the overall development towards data-driven science[1]. This development is based on progress in computation power, storage and networking connectivity, but also the introduction of technical standards and norms across the scientific disciplines and also science support infrastructures, such as digital libraries and repositories for the long term preservation of the record of science.

The emergence of data sets that are due to size and other factors exceedingly hard to manage and process by available computation infrastructures led in 2005 to the coining of the term Big Data[2]. Currently, six aspects are attributed to Big Data[3], of which veracity (the degree to which data and software is trustworthy due to transparency and provenance) is crucial for the significance of PID in data-driven science and the OSGeo Foundation.

2. MAIN PART

2.1 The OSGeo Foundation

Since the turn of the Millennium, individuals have formed bottom up grassroots networks to share their experiences with existing of newly created geospatial open source software tools. This began with the founding of national organisations for specific software tools [4], which eventually merged and evolved into international volunteer based software projects. This development culminated in the establishment of the OSGeo Foundation in 2006, which serves as an umbrella organisation of software communities which share common values and standards.

The OSGeo Foundation has created a growing interlinked continuum, consisting of software projects, committees, interest groups of people, but also knowledge, information and supporting infrastructure (Tzotzos, 2021). OSGeo consists currently of over 500 elected Charters Members, about 1,500 website members, and over 36,000 unique mailing list subscribers[5]. The OSGeo GeoForAll network[6] of over 100 tertiary education institutions provides certified geospatial education based on Open Science Standards.

The Foundation actively supports the concepts of open science, including open access, open source, open standards and open education. Figure 1 summarizes the key aspects of open science.

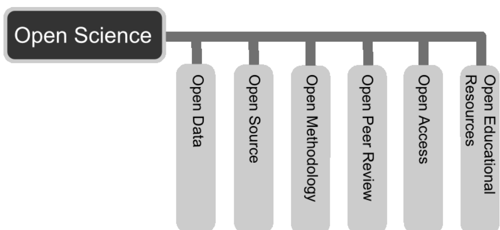

Figure 1. The six components of Open Science: Open Data, Open Source, Open Methodology, Open Peer Review, Open Access and Open Educational Resources (Source: Wikipedia)

A core concept of OSGeo since its beginning is the voluntary assessment of software projects and their communities regarding best practices for sustainable open project and community

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[1] The Fourth Paradigm: Data-Intensive Scientific Discovery (Hey et al., 2009)
[2] `https://datafloq.com/read/big-data-history/`
[3] Volume, velocity, variety, veracity, value and variability
[4] e.g., FOSSGIS e.V., `https://de.wikipedia.org/wiki/FOSSGIS`
[5] `https://docs.google.com/presentation/d/1brbBb7-sKRI6U4dZ7LKnBT_-NnWzyS2TaZqVXzy8RDo`
[6] `https://www.osgeo.org/initiatives/geo-for-all/` (Mitasova et al., 2017)

management. Projects who wish to be assessed can undergo the OSGeo graduation process supported by a designated mentor and, following successful graduation, are officially recognised as OSGeo projects. Graduated OSGeo projects are bundled into several OSGeo umbrella projects like OSGeoLive[7] or OSGeo4W[8], which merge multiple projects, data and documentation to provide users with one stop shop access to propagate the mixing bowl approach of OSGeo to combine several software tools for a task or workflow.

Figure 2 depicts the key concepts currently addressed in incubation, which overlap with the key concepts of Open Science (Figure 1). These best practices and community standards for successful graduation are not static but continue to be improved and updated by the OSGeo community.

Of the currently 71 projects associated with OSGeo, 21 have successfully graduated. Recognition as a quality-tested OSGeo project serves as decision support for potential users, developers and especially early career scientists when making strategic decisions about which software platform to choose for their work. While all open source projects allow software users to harness their powers ("standing on the shoulders of Giants" (Chen, 2003)), it is important to assess whether the choice made is sustainable and reliable in the long term.

The OSGeo System Administration Committee[9] provides infrastructure support and facilities information: The OSGeo software projects continue to evolve by migrating to new technical infrastructures, when necessary to sustain the continuation of the projects by state of the art IT infrastructures.

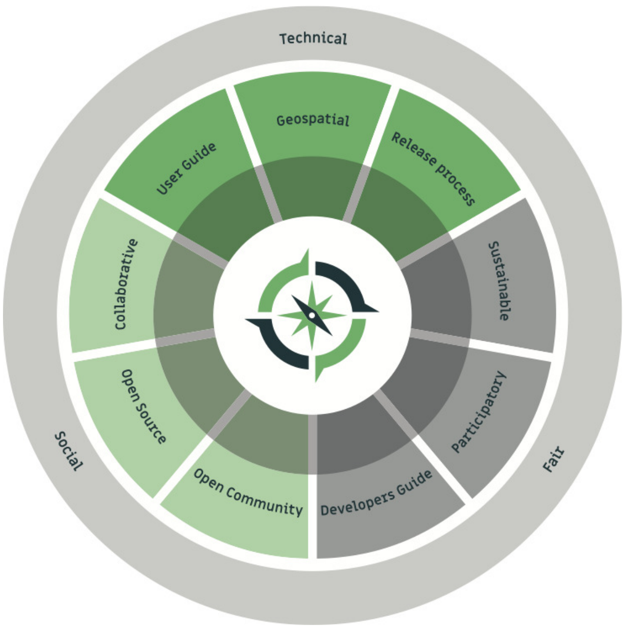

Figure 2. Diagram of the core topics assessed by the OSGeo incubation process (Source: OSGeo.org)

2.2 FAIR Principles and Open Science

Open Science, which is endorsed by OSGeo, calls for a maximum of openness and transparency in science (Konrad et al., 2019). The development of a less complete but flexible and sustainable framework began in 2014, acknowledging current constraints and limitations in science, research and publishing: For this, the acronym FAIR was introduced for a set of guiding principles to make digital research output Findable, Accessible, Interoperable, and Reusable. The FAIR principles for research data were published by the FORCE11 group in 2016 (Wilkinson et al., 2016).

The original FAIR principles apply both to research data and software by considering both as digital research objects. However, there are differences like usability lifespan, reliance on supporting software environments for execution and also code evolution and versioning, which distinguish research code from data. This led to the release of more specialised FAIR principles for research software (Chue Hong et al., 2021).

It is necessary to distinguish between novel innovative, potentially fragile research software which is created as part of the scientific process, to answer a research question or to collect new data on the one side, and stable well established software which is used for scientific purposes.

A key factor for data-driven science is the availability of open source software tools like the OSGeo software projects, which can be used as both reliable tools for science, but also as a foundation and proving ground to base novel research code (Mineault and Nozawa, 2021), standing on the shoulders of giants.

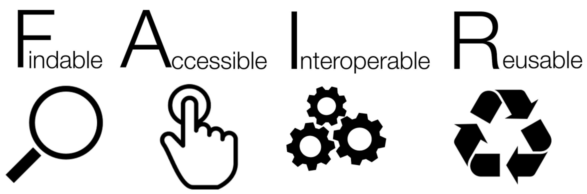

Figure 3. FAIR data principles: Findable, Accessible, Interopeable, Reusable. (Source: Wikipedia, © SangyaPundir CC-BY-SA)

2.3 Persistent Identifiers for Open and FAIR

Since the advent of the Internet and the World Wide Web, Universal Resource Locators (URL) have become a common standard to reference digital web resources. An URL specifies its location on a computer network and a mechanism for retrieving its digital content. However, URLs were not intended as a sustainable practice for scientific referencing and citation because they are by design guaranteed to eventually break once the referenced resource is transferred to another web address[10]. The amount of broken URL in the OSGeo wiki[11] and e-mail archives[12] is continuously growing, as content moves to other websites or is no longer kept online. This applies to references to all digital resources such as documents, data, software and audiovisual information.

The FAIR principles require unique and PID, as a key factor to establish open science. For this, PID must be well established, machine actionable, globally unique and interoperable. On the technical level several web-based identifiers match these

[7] `https://www.osgeo.org/projects/osgeolive/` (Emde, 2021)
[8] `https://www.osgeo.org/projects/osgeo4w/`
[9] `https://wiki.osgeo.org/wiki/SAC`

[10] i.e., the original URL cannot be resolved anymore and will create an error message (e.g., HTTP error 404)
[11] `https://wiki.osgeo.org/wiki/Main_Page`
[12] `https://lists.osgeo.org/mailman/listinfo`

requirements, including Handles[13], PURL[14], ARK[15], NBN[16], and Digital Object Identifiers (DOI)[17]. All these PID rely on an intermediary technical resolving mechanism and implemented practices: If a data object is moved to another location, the entity in charge of this action notifies the resolving authority to update the links pointing the PID to the actual location of the data object.

DOI have become widely accepted PID for digital objects. The first DOI for geospatial data were minted in 2004 (Klump et al., 2015). The background infrastructures for DOI resolving mechanisms, meta data and operations are managed and operated by several organisations, including CrossRef[18] and DataCite[19].

Similar to PID for digital objects, there are also PID for humans and organisations. For humans, the Open Researcher and Contributor ID (ORCID)[20] has gained wide acceptance since 2012 to uniquely identify authors and contributors of scholarly communication and reference their bibliographic output. For research organisations, a new identity standard is currently being introduced by the Research Organization Registry [21].

Since 2015, the Zenodo general-purpose open access repository[22] allows scientists and researchers from all fields of science to deposit research data sets and code if not other topical repository is available, providing a DOI for the deposit, linking it to their ORCID.

Registering a DOI upon successful deposition of a digital object in a repository requires the creation of a landing page. The landing page contains all provided metadata and a reference to the archived digital object. The DOI resolving mechanism ensures that all references to the DOI will reach the landing page. DOI and ORCID can be used immediately via web browsers, but also via API and programming languages, including R modules[23][24].

From the perspective of an software project community, there are three important relationships between the software project, software releases and DOI:

1. Reference to the overall project, effectively all releases of the software

2. Reference to the latest software release.

3. Reference a specific release of the software project

Until 2018, the depositing of a software release from a software repository had to be handled manually in Zenodo. In 2018[25] an improved technical workflow integration was released to enable automated depositing of new software versions (releases) for software repositories hosted on GitHub and linked to Zenodo.

During the initial use of such a setup is initially used to deposit a first software release in Zenodo, two DOI are created: A Concept DOI for the software project, representing it as an intellectual construct, and a Version DOI, for the specific software release. Following software releases will cause the creation (minting) of additional Version DOI, which will be tied to the Concept DOI of the project[26]. This satisfies all three relationships which are key for software project communities to adopt DOI.

2.4 Persistent Identifiers for OSGeo

2.4.1 DOI for OSGeo Conference Videos In 2014, the discovery of a historic informational video about GRASS GIS dating from 1987 introduced DOI to OSGeo. The video content was digitised by the German National Library TIB Hannover and added to the online collection of scientific audiovisual content (AV-Portal[27]). In this process, a DOI was minted to provide scientific citatation of the video (Inman, 1987) due to its significance as part of the scientific and technological record. This sparked further interest by OSGeo to investigate how to utilise and benefit from PID-enabled workflows (Löwe, 2014).

Since 2016, TIB Hannover collects continuously OSGeo conference recordings as a permanent service to the OSGeo communities. Pre-COVID the the collection grew annually by approximately 100 hours of video recordings, including preserving earlier conference recordings from transient platform such as Youtube and Vimeo. This allows to reference recordings from OSGeo conferences by DOI as part of the scientific record and to use them for education (Löwe et al., 2016). As of June 2022, the AV Portal contains 1,146 OSGeo-related videos from the years 2002, 2013 to 2021 (total running time: 466 hours)

2.4.2 DOI for OSGeo Software Projects Since 2017, the number of DOI registrations by OSGeo software projects has increased significantly. Currently, DOI are available for 19 software repositories[28] related to OSGeo. More than half of the officially graduated OSGeo software projects can already be referenced by DOI.

The first OSGeo project to register a DOI was the OSGeo Community Project rasdaman for its version 9.4.2 in late 2017 (Baumann, 2017). In 2019, the GMT project minted a DOI for release version 6.0.0 (Wessel et al., 2019). In 2021, DOI were registered by six OSGeo projects GeoServer (Aime et al., 2022a), GeoTools (Aime et al., 2022b), Mapserver (McKenna and PSC, 2021), GRASS GIS (Landa et al., 2022), MOSS (Reed et al., 2022), and PostGIS (McKenna and Team, 2021). In 2022, the pace further accelerated with eleven OSGeo project repositories registering DOI until the time of writing (June): actinia (Tawalika et al., 2022), GDAL (Rouault et al., 2022),

[13] `https://en.wikipedia.org/wiki/Handle$_$(computing)`
[14] `https://en.wikipedia.org/wiki/Persistent$_$uniform$_$resource$_$locator`
[15] `https://en.wikipedia.org/wiki/Archival$_$Resource$_$Key`
[16] `https://en.wikipedia.org/wiki/Uniform_Resource$_$Name`
[17] `https://en.wikipedia.org/wiki/Digital$_$object$_$identifier`
[18] `https://www.crossref.org/`
[19] `https://datacite.org/`
[20] `https://orcid.org/`
[21] `https://ror.org/`
[22] `https://zenodo.org/`
[23] `https://cran.r-project.org/web/packages/rorcid/index.html`
[24] `https://cran.r-project.org/web/packages/zen4R/index.html`
[25] `https://genr.eu/wp/cite/`
[26] e.g., the Concept DOI for the GRASS GIS project is `10.5281/zenodo.5176030`, while the Version DOI for the latest release GRASS GIS 8.2.0 is `10.5281/zenodo.6612307`. The first release is (Landa et al., 2021). Until now, sixteen software releases of GRASS GIS can be individually referenced by DOI.
[27] `https://av.tib.eu/`
[28] `https://wiki.osgeo.org/wiki/DOI`

GeoPaparazzi (Antonello and Franceschi, 2022a), gvSIG (Anguix et al., 2022), Mapbender (Emde, 2021), PROJ (Evenden et al., 2022), QGIS (Contributors, 2022), OSGeoLive (Emde, 2022a), OSGeoLive Documentation (Emde, 2022b), SMASH (Antonello and Franceschi, 2022b), HortonMachine (Antonello et al., 2022). Table 2 summarizes the numbers of DOI registrations by OSGeo projects over time.

The significant increase of DOI registrations by OSGeo project communities in 2021 and 2022 was caused by a book publication project (Kresse and Danko, 2022). For the standard reference Handbook of Geographic Information, originally published in 2009 (Kresse and Danko, 2009), a second updated edition had been under preparation since 2017. Due to the COVID pandemic, the project was delayed. This provided the opportunity to incorporate the emerging capabilities for DOI-based referencing of software projects and conference recordings. For this, the previously registered DOI of the rasdaman and GMT projects served as proofs of concept.

This was paralleled by an independent effort to establish the historical software project MOSS GIS as the first OSGeo heritage project. For this, the codebase of MOSS GIS, which had been stable since 1987, had to be salvaged, transferred in a OSGeo repository on GitHub[29] and preserved on Zenodo (Löwe et al., 2021). This process allowed to further explore and document the automated integration of OSGeo repositories, Zenodo and ORCID accounts of OSGeo project members.

All OSGeo projects were approached, which were to be featured in the publication project but hadn't registered DOI yet. The majority was able to register DOI in time to enable future references to their code bases by the readers of the second Edition of the Handbook of Geographic Information with an estimated shelf time of a decade.

OSGeo Project	Concept DOI	Year
actinia	10.5281/zenodo.5865317	2022
GDAL	10.5281/zenodo.5884351	2022
Geopaparazzi	10.5281/zenodo.5881915	2022
GeoServer	10.5281/zenodo.5854561	2021
GeoTools	10.5281/zenodo.5854653	2021
GMT	10.5281/zenodo.3407865	2019
GRASS GIS	10.5281/zenodo.5176030	2021
gvSIG	10.5281/zenodo.5849091	2022
HortonMachine	10.5281/zenodo.5881778	2022
Mapbender	10.5281/zenodo.5887014	2022
MapServer	10.5281/zenodo.5842012	2021
MOSS	10.5281/zenodo.5140318	2021
OSGeoLive	10.5281/zenodo.5884641	2022
OSGeoLive Docum.	10.5281/zenodo.5884859	2022
PostGIS	10.5281/zenodo.5879631	2021
PROJ	10.5281/zenodo.5884394	2022
QGIS	10.5281/zenodo.5869837	2022
rasdaman	10.5281/zenodo.1040170	2017
SMASH	10.5281/zenodo.5882070	2022

Table 1. Alphabetical list of OSGeo projects which have registered DOI (June 2022).

2.5 Benefits and Reality Checks

OSGeo projects, their software repositories and software releases can be cited by DOI, which already applies for about half of the graduated OSGeo projects. This might turn into a critical mass for the adoption of DOI by further OSGeo projects, provided tangible advantages can be demonstrated. This section summarizes the currently available or emerging DOI-enabled services and resulting benefits for OSGeo project communities.

Year	OSGeo Project DOI
2017	rasdaman
2018	-
2019	GMT
2020	-
2021	6 project repositories
2022	11 project repositories

Table 2. Annual rate of of OSGeo project repositories registering DOI from 2017 to June 2022.

2.5.1 Reference by Concept DOI and Version DOI Transient URL-based can now be superseded by DOI-based references to OSGeo repositories. The automated depositing of software releases in the open access repository Zenodo ensures long term preservation when the GitHub infrastructure has ceased to exist. In this publication, this approach has been used to future-proof the entries of the reference section for long term availability.

2.5.2 Citation Formatting Services Several web-based citation formatting service[30][31] can be used to derive citations in a wide variety of citation styles[32] and languages based on DOI metadata. This applies both for Concept DOI and Version DOI of OSGeo projects. Such output can be used manually as formatted citation strings or as data sets[33] for citation databases. For this publication, these services were used as input for bibliography management with BibTEX.

This is a significant improvement from previous internal capabilities provided by OSGeo software, like the GRASS GIS add-on g.citation[34], which provided only a limited basic range of citation formats.

2.5.3 Related Identifiers and Credit Propagation DOI and other PID[35] can be linked to each other by including related identifiers to the PID metadata. This allows to relate DOI of OSGeo software to other software, data and resources such as conference video recordings by DOI or other PID.

A significant number of OSGeo projects rely of each other either as integrated software libraries or as parts of umbrella projects such as OSGeo live. The implementation of related PID, such as Version DOI, will allow to better analyse and map out these interrelations and how they evolve over time. Relations which can be included in PID metadata include references, supplements, cites, publishes, new-version, continues, describes, reviews, copies, source of, replaces, is identical and is alternate identifier for.

Relating PID also enables credit propagation. If a Version DOI of an OSGeo project is referenced in a publication, which is cited by a second publication, the citation score will be added for the Version DOI of the first publication, but it can also

[29] `https://github.com/OSGeo/MOSS`

[30] `https://citation.crosscite.org/`
[31] `https://www.doi2bib.org/`
[32] `https://citationstyles.org/`
[33] e.g., XML, JSON, bib and others
[34] `https://github.com/OSGeo/grass-addons/tree/grass8/src/general/g.citation`
[35] Handle, ARK, PURL, ISSN, ISBN, PubMed ID, PubMed Central ID, ADS Bibliographic Code, arXiv, Life Science Identifiers (LSID), EAN-13, ISTC, URN and URL

propagate to OSGeo contributors, based on their ORCID. By this OSGeo contributors can receive tangible scientific credit for their project-related volunteer work.

2.5.4 Reality Check The service quality of the described service assets is under development and remains heterogeneous. While core services such as DOI-resolving have proven to be fully operational, emerging services like citation formatting services and credit propagation can not be considered fully reliable yet[36]. Of the 19 OSGeo Concept DOI covered in this article, the formatting service returned BibTEX @book entries for 18 Concept DOI and an @article entry for one Concept DOI (rasdaman project). According to the BibTEX entry specification[37], the correct item style should have been @item, which was not generated. Since the BibTEX formatting style of ISPRS supports only DOI or URL for @articles, the encountered breaks in the automated workflow had to be manually fixed.

To gauge the currently available service levels and capabilities, we refer to the Technology Readiness Level (TRL)[38],[39] scale to asses the maturity of technologies and workflows. Figure 4 provides an overview over the TRL levels 1 to 7, ranging from fundamental research (TRL 1) to fully operational proven services (TRL 7). The core DOI based resolving services are fully mature can be considered TRL 9 (proven system operations). However, service offerings such as credit propagation and formatting services must still be considered TRL 7 (development) or below (technology demonstrators), as they provide varying output. This is not necessarily caused by the implemented technical workflows, but lack of best practices for metadata deposition in the PID landing pages[40].

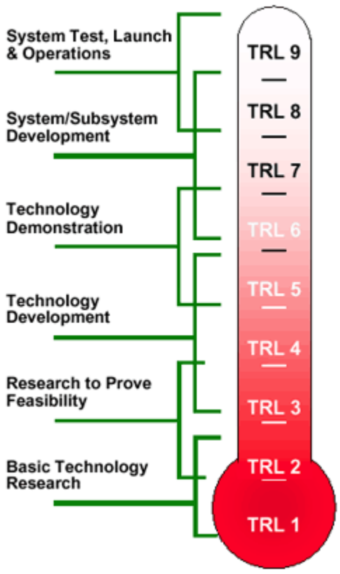

Figure 4. The Techological Readiness Level Scale (Source: Wikipedia © NASA/Airspace Systems (AS), public domain)

[36] For this publication we used the Crosscite formatting service to create BibTEX entries.

[37] https://www.bibtex.com/e/entry-types

[38] https://en.wikipedia.org/wiki/Technology_readiness_level

[39] https://www.iso.org/standard/56064.html

[40] While all DOI related to OSGeo software projects in the reference section of this publication were processed in the same manner, the information content shown in the reference section varies significantly.

3. THE SHAPE OF THINGS TO COME

In this section we sketch out several likely near-future scenarios, based on the range of PID-based service offerings, which will provide the greater shape of things to come both for OSGeo and FAIR based data-driven science.

3.1 PID-based Citation becomes Mainstream

While DOI-based reference and citation for software has been technically implemented, it still ahs to be widely endorsed, practiced and enforced as good practice by publishers. For this the author guidelines for manuscript preparation provided by publishers[41] will be extended for code citation guidelines (Chue Hong et al., 2019).

3.2 Advancing Infrastructures and Services

Software releases which predate the initial DOI registration of a software project currently have to be handled manually for every single historic release. OSGeo projects like GRASS GIS (Neteler et al., 2012) and MOSS have development histories spanning decades. For these cases, manual action to complete the version record in Zenodo would be prohibitive. Automated methods will have to be developed for such retro-depositing tasks. In this context, there exists also the challenge how to pay due credit to former software developers, of whom no other record than their usernames have been preserved.

In addition to the established integration of GitHub based software repositories with the Zenodo open access repository, a diversification both for the range of open access repositories but also software repositories is needed: Software projects that are developed on code repository platforms beyond GitHub, such as JIRA, currently have to mirror software releases on GitHub to benefit from DOI use.

3.3 New Best Practices for OSGeo and Beyond

Lessons learned from consultations with the OSGeo software projects, which have already registered DOI need to be compiled and widely shared. This includes definitions of new generic roles within the projects[42] and integration into long term planning and preparation cycle for software releases.

Other communities are expected to also benefit from this, as the currently available tutorials about PID for socftware focus primarily on research software which is developed from scratch, but not established software projects.

Until now DOI for software has been adopted by the OSGeo projects in a bottom up manner. As the best practices for the OSGeo incubation continue to evolve, best practices for PID and software citation will likely become part of the key incubation topics roster, adding a top-down approach to help new OSGeo projects improve. This is expected to help attract future generations of users and developers from academia to join OSGeo project communities, motivated by to the positive impact of their scientific track record.

The trend towards cloud computing has opened new ecotopes for OSGeo projects. The actinia project (Tawalika et al., 2022) extends the evolution of traditional projects GIS such as GRASS

[41] e.g., https://www.isprs.org/documents/orangebook/app5.aspx

[42] e.g. the maintainer role for Zenodo-related metadata

GIS into cloud computing for scalable, distributed, high performance processing of geographical data. It provides a REST API to e.g. process satellite images, time series of satellite images, arbitrary raster data with geographical relations and vector data. Deployed in the cloud, this offers a series of advantages: actinia is scalable and processed in a distributed manner large quantities of Earth Observation (EO) and geodata. It is addressing the paradigm of computing next to the data without the need to bother with the low-level management of large amounts of data anymore. For complex cloud based workflows, PID are expected to become a key factor to transparently reference and cite data-driven workflows, including software environments, processed data and resulting output (Schramm et al., 2021).

4. CONCLUSIONS

Persistent identifiers (PID) and the supporting technical infrastructures have become established as crucial factors for the advancement of data-driven science, fostered by the FAIR principles as part of open science: Research data, research software but also software used for research can be referenced today by PID.

The automated integration of software releases on GitHub-based software repositories with code and meta data depositing in the Zenodo open access archive brings tangible benefits by new service offerings to software communities, such as the OSGeo software projects.

The software projects of the OSGeo foundation have begun in a bottom up fashion to adopt DOI based software citation and integration with open access repositories. This approach might eventually be added as recommended practice to the OSGeo incubation canon for sustainable community projects both in science, industry and society. In the meantime, the growing usage of DOI-based software citation in OSGeo will be a driver to attract early career scientists, due to the new tangible scientific credit for research code and software project work.

REFERENCES

Aime, A., Barsballe, T., Garnett, J., NielsCharlier, Romagnoli, D., Smith, K., Fabiani, A., Caradoc-Davies, B., Mbarto, Oliveira, N., Hards, B., Taba90, Pumphrey, M., Roldan, G., Turton, I., Prins, M., Ikeoka, S., Gasdorf, F., Miño, F., Deoliveira, J., Tucker, D., Angreani, R., Otero, J. M., , I., Savazzi, D., Tajariol, E., N-Lagomarsini, Hughes, J., Smythe, P., Hartell, B., 2022a. geoserver/geoserver: GeoServer 2.20.4. https://doi.org/10.5281/zenodo.5854561.

Aime, A., Brown, A., Fabiani, A., Wöstmann, A., Caradoc-Davies, B., Hards, B., Walker, B., Romagnoli, D., Tucker, D., Winslow, D., Tajariol, E., Miño, F., Gasdorf, F., Roldan, G., Mayo, I., Turton, I., Schneider, I., Deoliveira, J., Erickson, J., Eichar, J., Hughes, J., Garnett, J., Jrbeckwith, Jwood106, Morandini, L., Leslie, M., Mbarto, Mcrmcr, Antonello, A., Pazos, M., Prins, M., N-Lagomarsini, NielsCharlier, Oliveira, N., Parma, A., Costa, S., Angreani, R., Giannecchini, S., Smith, K., Uhrig, S., Savazzi, D., Kalén, M., Taba90, Barsballe, T., , J., Vick, D., , V., 2022b. GeoTools. https://doi.org/10.5281/zenodo.5854653.

Anguix, A., Carrera, M., Cerro, J. D., Martínez, O., Higón, J. V., Peñarrubia, F. J., Martínez, C., Rodrigo, J., Díaz, F., Olivas, J., Brodín, I., 2022. gvSIG. https://doi.org/10.5281/zenodo.5849091.

Antonello, A., Franceschi, S., 2022a. Geopaparazzi. https://doi.org/10.5281/zenodo.5881915.

Antonello, A., Franceschi, S., 2022b. SMASH. https://doi.org/10.5281/zenodo.5882070.

Antonello, A., Franceschi, S., Riccardo, R., 2022. Hortonmachine. https://doi.org/10.5281/zenodo.5881778.

Baumann, P., 2017. Rasdaman - Raster Data Manager. https://doi.org/10.5281/zenodo.1040170.

Chen, C., 2003. On the Shoulders of Giants. *Mapping Scientific Frontiers: The Quest for Knowledge Visualization*, 135–166. https://doi.org/10.1007/978-1-4471-0051-5_5.

Chue Hong, N. P., Allen, A., Gonzalez-Beltran, A., de Waard, A., Smith, A. M., Robinson, C., Jones, C., Bouquin, D., Katz, D. S., Kennedy, D., Ryder, G., Hausman, J., Hwang, L., Jones, M. B., Harrison, M., Crosas, M., Wu, M., Löwe, P., Haines, R., Edmunds, S., Stall, S., Swaminathan, S., Druskat, S., Crick, T., Morrell, T., Pollard, T., 2019. Software Citation Checklist for Authors. *Zenodo*. https://zenodo.org/record/3479199.

Chue Hong, N. P., Katz, D. S., Barker, M., Lamprecht, A.-L., Martinez, C., Psomopoulos, F. E., Harrow, J., Castro, L. J., Gruenpeter, M., Martinez, P. A., Honeyman, T., 2021. FAIR Principles for Research Software (FAIR4RS Principles). *Research Data Alliance*. https://rd-alliance.org/group/fair-research-software-fair4rs-wg/outcomes/fair-principles-research-software-fair4rs-0.

Contributors, Q., 2022. QGIS. https://doi.org/10.5281/zenodo.5869837.

Emde, A., 2021. OSGeoLive: Your Open Source Geospatial Toolkit. https://av.tib.eu/media/52538.

Emde, A., 2022a. OSGeoLive. https://doi.org/10.5281/zenodo.5884641.

Emde, A., 2022b. OSGeoLive Documentation. https://doi.org/10.5281/zenodo.5884859.

Evenden, G. I., Rouault, E., Warmerdam, F., Evers, K., Knudsen, T., Butler, H., Taves, M., Schwehr, K., Sales de Andrade, E., Karney, C., Couwenberg, S., Dawson, N., Snow, A. D., Jimenez Shaw, J., 2022. PROJ. https://doi.org/10.5281/zenodo.5884394.

Hey, T., Tansley, S., Tolle, K., Gray, J., 2009. *The Fourth Paradigm: Data-Intensive Scientific Discovery*. Microsoft Research.

Inman, R. J., 1987. GRASS. https://av.tib.eu/media/12963.

Klump, J., Huber, R., Diepenbroek, M., 2015. Doi for geoscience data - how early practices shape present perceptions.

Konrad, S., Enescu, I. I., Pernas, L. D., Fraefel, M., Plattner, G.-K., Meile, R., Haas-Artho, D., Kramer, T., Hägeli, M., Bont, L., 2019. Open Science, Knowledge Sharing and Reproducibility as Drivers for the Adoption of FOSS4G in Environmental Research. https://av.tib.eu/media/43572.

Kresse, W., Danko, D. M. (eds), 2009. *Springer Handbook of Geographic Information*. Springer Handbooks, 1 edn, Springer, Berlin, Germany.

Kresse, W., Danko, D. M. (eds), 2022. *Springer Handbook of Geographic Information*. Springer Handbooks, 2 edn, Springer, Berlin, Germany.

Landa, M., Neteler, M., Metz, M., Petrasova, A., Glynnc, HamishB, Petras, V., Huhabla, Cho, H., Delucchi, L., , P., Barton, M., Chemin, Y., Zigo, T., Nartišs, M., Ostepok, Kudrnovsky, H., Mlennert, Nilason, Kyngesburye, W., Blumentrath, S., Kladivova, L., Aghisla, Andreo, V., Jacobson, D., Ovsienko, Denis and, M., MITASOVA, H., Weinmann, A., Mmacata, 2021. OSGeo/grass: GRASS GIS 7.8.6RC2. https://doi.org/10.5281/zenodo.5176031.

Landa, M., Neteler, M., Metz, M., Petrasova, A., Glynnc, HamishB, Petras, V., Huhabla, Cho, H., Delucchi, L., Zambelli, P., Barton, M., Zigo, T., Chemin, Y., Nartišs, M., Ostepok, Kudrnovsky, H., Larsson, N., Lennert, M., Blumentrath, S., Kladivova, L., Kyngesburye, W., Ghisla, A., Andreo, V., Jacobson, D., Ovsienko, D., Haedrich, C., Di Leo, M., Mitasova, H., Tawalika, C., 2022. OSGeo/grass: GRASS GIS 8.2.0. https://zenodo.org/record/5176030.

Löwe, P., Nartišs, M., Reed, C. N., 2021. Raiders of the Lost Code: Preserving the MOSS Codebase - Significance, Status, Challenges and Opportunities. https://doi.org/10.5194/egusphere-egu21-5492.

Löwe, P., 2014. GRASS GIS, Star Trek and old Video Tape – a reference case on audiovisual preservation for the OSGeo communities. *Unpublished*. http://rgdoi.net/10.13140/2.1.2983.6801.

Löwe, P., Plank, M., Kraft, A., Dreyer, B., 2016. OSGeo conference videos as a resource for scientific research: The TIB—AV Portal. https://av.tib.eu/media/20452.

McKenna, J., PSC, M., 2021. MapServer. https://doi.org/10.5281/zenodo.5842012.

McKenna, J., Team, P., 2021. PostGIS 3.2.0, The Olivier Courtin Release. https://doi.org/10.5281/zenodo.5879631.

Mineault, P., Nozawa, K., 2021. patrickmineault/codebook: 1.0.0. https://doi.org/10.5281/zenodo.5796873.

Mitasova, H., Petras, V., Petrasova, A., 2017. State of geoforall. FOSS4G, Open Source Geospatial Foundation $OSGeo. Lastaccessed: 08Jun$2022.

Neteler, M., Bowman, M., Landa, M., Metz, M., 2012. GRASS GIS: A multi-purpose open source GIS. *Environmental Modelling & Software*, 31, 124–130.

Reed, C. N. I., Katz, S., Frosh, R., Davidson, J., Taylor, A., Lee, J., 2022. OSGeo/MOSS: MOSS Archive 1.2.3. https://doi.org/10.5281/zenodo.5140318.

Rouault, E., Warmerdam, F., Schwehr, K., Kiselev, A., Butler, H., Łoskot, M., Szekeres, T., Tourigny, E., Landa, M., Miara, I., Elliston, B., Kumar, C., Plesea, L., Morissette, D., Jolma, A., Dawson, N., 2022. GDAL. https://doi.org/10.5281/zenodo.5884351.

Schramm, M., Pebesma, E., Milenković, M., Foresta, L., Dries, J., Jacob, A., Wagner, W., Mohr, M., Neteler, M., Kadunc, M., Miksa, T., Kempeneers, P., Verbesselt, J., Gößwein, B., Navacchi, C., Lippens, S., Reiche, J., 2021. The openEO API–Harmonising the Use of Earth Observation Cloud Services Using Virtual Data Cube Functionalities. *Remote Sensing*, 13(6), 1125. http://dx.doi.org/10.3390/rs13061125.

Tawalika, C., Weinmann, A., Riembauer, G., Metz, M., Haas, J., Jansen, M., Herrera Maldonado, J. A., Gebbert, S., Neteler, M., 2022. actinia-core. https://doi.org/10.5281/zenodo.5865317.

Tzotzos, A., 2021. Open Source Geospatial Foundation (OSGeo). https://av.tib.eu/media/55248.

Wessel, P., Luis, J. F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H. F., Tian, D., 2019. The Generic Mapping Tools version 6. https://doi.org/10.5281/zenodo.3407866.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., Gonzalez-Beltran, A., Gray, A. J., Groth, P., Goble, C., Grethe, J. S., Heringa, J., 't Hoen, P. A., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, 3(1). http://dx.doi.org/10.1038/sdata.2016.18.