Reproducible research and GIScience: an Evaluation using AGILE conference papers

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ABSTRACT

The demand for reproducibility of research is on the rise in disciplines concerned with data analysis and computational methods. In this work existing recommendations for reproducible research are reviewed and translated into criteria for assessing reproducibility of articles in the field of geographic information science (GIScience). Using a sample of GIScience research from the Association of Geographic Information Laboratories in Europe (AGILE) conference series, we assess the current state of reproducibility of publications in this field. Feedback on the assessment was collected by surveying the authors of the sample papers. The results show the reproducibility levels are low. Although authors support the ideals, the incentives are too small. Therefore we propose concrete actions for individual researchers and GIScience conference series to improve transparency and reproducibility, such as imparting data and software skills, an award, paper badges, author guidelines for computational research, and Open Access publications.

1 INTRODUCTION

A ”reproducibility crisis” has been observed and discussed in several scientific disciplines such as economics (Ioannidis, Stanley, and Doucouliagos, 2017), medical chemistry (Baker, 2017), or neuroscience (Button et al., 2013) and even across disciplines on scientific studies in general (Ioannidis, 2005). It stems from researchers facing challenges of understanding and re-creating results of others, a situation closely connected with data-driven and algorithm-based research. A reproducibility crisis has not yet been associated with geographic information science (GIScience) despite the fact that data and algorithms are becoming more relevant in the field. Although failures to reproduce are not a topic of broad and common interest in GIScience, the goal should be to prevent a crisis instead of reacting to one. Given this motivation, we aim to adapt the observations and

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challenges of reproducible research from other disciplines to the GIScience community, represented by AGILE conferences and the AGILE members. AGILE stands for Association of Geographic Information Laboratories in Europe; this association organises annual conferences on GIScience topics since 1998[1]. The conference series's broad topical scope and its wide acceptance in the respective community make it a reasonable starting point for our investigation of the level of reproducibility in GIScience. This publication continues a collaboration started at the AGILE 2017 pre-conference workshop "Reproducible Geosciences Discussion Forum"[2].

In this work, we first review papers from other disciplines, which provide recommendations on how to make research more transparent and reproducible. This literature study forms the basis for criteria to systematically evaluate a sample of 32 AGILE conference papers of the last eight years. From this evaluation and the lessons learned by others, we formulate recommendations for the AGILE community, ranging from individual researcher's practises to conference organisation. Because of its international reach, broad range of topics, and long-sustained community, we argue that AGILE is in a unique position to take a leading role to promote reproducibility in GIScience. The following research questions (RQs) structure the remainder of this article:

RQ 1 *What are general criteria for reproducible research?*

RQ 2 *What are key criteria for reproducible research in GIScience?*

RQ 3 *How do AGILE conference papers meet these reproducibility criteria?*

RQ 4 *What strategies could improve reproducibility in AGILE contributions and GIScience in general?*

2 RELATED WORK

Reproducible research is a frequently discussed topic in editorials and viewpoint articles in high-impact journals (cf. Section 3.2). Extensive studies on the state of reproducibility have been conducted in some domains, e.g. in computer systems research (Collberg and Proebsting, 2016)[3] or bioinformatics (Hothorn and Leisch, 2011). Brunsdon (2016) and Giraud and Lambert (2017) discuss the topic in quantitative geography and cartography respectively; Ostermann and Granell (2017) examine the domain of volunteered geographic information (VGI). No comprehensive study of reproducibility in the GIScience domain has been conducted.

Even though recent studies (Tenopir et al., 2011; Ioannidis, 2014) highlight an increased awareness of and willingness for open research, they also draw attention to persistent issues and perceived risks associated with data sharing and publication, such as the lack of rewards and the concern to lose recognition in a competitive academic environment. Beyond individual concerns, there are systematic impediments. Some (Stodden, McNutt, et al., 2016; McNutt, 2014; Ioannidis, 2014) remark reproducible research is not an individual researcher's but a multi-actor endeavour, which requires a collective mind shift within the scientific community. Funding agencies, research institutions, publishers, journals, and conferences are all responsible to promote reproducible research practises. Existing examples[4] are remarkable yet in the big picture scarce and testimonial.

[1] https://agile-online.org/index.php/conference/past-agile-conferences
[2] http://o2r.info/agile-2017/
[3] See also project website http://reproducibility.cs.arizona.edu/
[4] Journals welcoming reproducible papers:

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3 MATERIALS & METHODS

3.1 What is Reproducibility?

Given the distinct nature and variety of research practises, the term reproducibility has been used with varying meanings and may stand for repeatability, robustness, reliability or generalisability of scientific results (Editorial, 2016). There has been some confusion about contradictory meanings in the literature (see for example Mark Liberman's "Replicability vs. reproducibility"[5]). Wikipedia's definition[6] is widely used to distinguish both terms:

> Reproducibility is the ability to get the same research results using the raw data and computer programs provided by the researchers. A related concept is replicability, meaning the ability to independently achieve similar conclusions when differences in sampling, research procedures and data analysis methods may exist.

Leek and Peng (2015) similarly define reproducibility as the ability to compute exactly the same results of a study based on original input data and details of the analysis workflow. They refer to replicability as obtaining similar conclusions about a research question derived from an independent study or experiment. A Editorial (2016) defines reproducibility as achieved when "another scientist using the same methods gets similar results and can draw the same conclusions". Stodden, McNutt, et al. (2016, p. 1240) base their reproducibility enhancement principles on "the ability to rerun the same computational steps on the same data the original authors used".

While most literature shares a common understanding of what these two concepts are, the application by the scientific communities is still inconsistent and leads to different methods and dissemination conventions, which both influence and are shaped by particular interpretations of reproducibility and replicability. In the field of GIScience, Ostermann and Granell (2017, p. 226) argue that "a reproduction is always an exact copy or duplicate, with exactly the same features and scale, while a replication resembles the original but allows for variations in scale for example". Hence, reproducibility is exact whereas replicability means confirming the original conclusions, though not necessarily with the same input data, methods, or results.

This paper focuses on reproducibility in the context of conference publications and adopts the described consensus in the following definition:

> A reproducible paper ensures a reviewer or reader can recreate the computational workflow of a study or experiment, including the prerequisite knowledge and the computational environment. The former implies the scientific argument to be understandable and sound. The latter requires a detailed description of used software and data, and both being openly available.

3.2 Recommendations and Suggestions in Literature

Scientists from various disciplines suggest guidelines for open and reproducible research considering the specific characteristics of their field, e.g. Sandve et al. (2013) for life sciences, McNutt (2014)

Information Systems (https://www.elsevier.com/journals/information-systems/0306-4379), Vadose Zone Journal https://dl.sciencesocieties.org/publications/vzj/articles/14/10/vzj2015.06.0088), GigaScience (https://academic.oup.com/gigascience/pages/instructions_to_authors), JASA (http://www.sph.umn.edu/news/wolfson-named-reproducibility-editor-asa-statistics-journal/)

[5] http://languagelog.ldc.upenn.edu/nll/?p=21956

[6] https://en.wikipedia.org/wiki/Reproducibility

for field sciences, and Gil et al. (2016) for the geoscientific paper of the future. Our goal is to identify common recommendations applicable across research fields, including GIScience.

Suggestions in the investigated papers were categorised according to four aspects: data concerns all inputs; methods cover everything on the analysis of data, e.g. algorithms, parameters, and source code; results include (intermediate) data and parameters as well as outcomes such as statistics, maps, figures, or new datasets; structure considers the organisation and integration of the other aspects. While some of the publications focus on specific aspects such as data (Gewin, 2016), code (Stodden and Miguez, 2014), workflow semantics (Scheider, Ostermann, and Adams, 2017), and results (Sandve et al., 2013), others provide an all-embracing set of research instructions (Stodden, McNutt, et al., 2016; Nosek et al., 2015; Gil et al., 2016).

3.2.1 Data

A recurrent aspect is making data accessible for other researchers (cf. Reichman, M. B. Jones, and Schildhauer, 2011), ideally as archived assets having a Digital Object Identifier (DOI) and supplemented by structured metadata (Gewin, 2016). Stodden, McNutt, et al. (2016) consider legal aspects, such as sharing data publicly under an open license to clarify reusability. Further recommendations refer to scientific practises, for example, citation standards to ensure proper acknowledgement (Nosek et al., 2015), fostering data transparency (McNutt, 2014), and open data formats to mitigate potentially disappearing proprietary software (Gewin, 2016). According to Reichman, M. B. Jones, and Schildhauer (2011), journals and funders should include data sharing in their guidelines.

3.2.2 Methods

Sharing used or developed software is a key requirement (Sandve et al., 2013) concerning methods. It should be published by using persistent links (Stodden, McNutt, et al., 2016; Gil et al., 2016) and descriptive metadata (Reichman, M. B. Jones, and Schildhauer, 2011). Similar to data, open licensing (Barba, 2016) and proper credits (Stodden, McNutt, et al., 2016) are important. Researchers can accomplish software transparency by using version control systems (cf. Sandve et al., 2013). Transparency mandates using open source instead of proprietary software (Steiniger and Hay, 2009). Since full computational reproducibility can depend on exact software versions (Gronenschild et al., 2012), the computational environment needs to be reported (cf. Stodden, McNutt, et al., 2016; Gil et al., 2016). Further software-specific recommendations are workflow tracking (Stodden and Miguez, 2014) and keeping a record analysis parameters (Gil et al., 2016). Sandve et al. (2013) suggest avoiding manual data manipulation steps, instead using scripts to increase transparency in data preprocessing.

3.2.3 Results

Sandve et al. (2013) focuses on results-related guidelines such as storing intermediate results and noting seeds if computations include randomness. Journals should conduct a reproducibility check prior to publication (Stodden, McNutt, et al., 2016). Collberg and Proebsting (2016) propose funding explicitly for making research results repeatable. Barba (2016) describes the contents and benefits of a ”reproducibility package” to preserve results.

3.2.4 Stucture

An overarching structure for all aspects of research provides additional context, but none of the suggestions is widely established, for example Gentleman and Lang (2007) using programming

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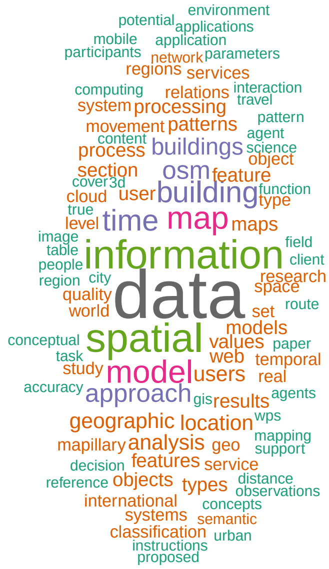

place	word	n	# papers
1	data	1058	31
2	information	589	32
3	spatial	577	30
4	map	411	25
5	model	411	25
6	building	381	24
7	time	378	30
8	approach	297	32
9	osm	292	8
10	buildings	266	15
11	geographic	249	28
12	location	239	26
13	analysis	229	28
14	users	225	19
15	results	207	30
16	web	206	21
17	models	202	20
18	values	202	23
19	patterns	196	16
20	maps	189	20

Figure 1. Word cloud of test corpus papers (left), scaled and coloured by number of occurrence, based on 96 unique words with at least 100 occurrences; top words based on overall occurrence and number of papers including the word at least once (right)

language packaging mechanisms, Bechhofer et al. (2013) using Linked Data, or Nüst et al. (2017) using nested containers.

3.2.5 Summary

Most recommendations and suggestions to foster open research address data and methods. Particularly methods cover a broad range of aspects including recommendations on data preprocessing, the actual analysis, and the computational environment. Results receive less attention, possibly because they are strongly connected with other aspects. While most of the recommendations address authors, only few target journals and research institutions.

3.3 The Paper Corpus

We consider the AGILE conference series publications to be a representative sample of GIScience research because of the conference's broad topical scope. Since 2007, the AGILE conference has a full paper track (cf. Pundt and Toppen, 2017) and a short paper track with blind peer review. The latter is published for free on the AGILE website. Legal issues (full paper copyrights lie with the publisher[7]) and practical considerations (assessment of reproducibility is a manual time-consuming process; old publications introduce bias because of software unavailability) led to the restriction of our evaluation to nominees for the "best full and short paper" awards for 2010, and 2012 to 2017 (no records for a best paper award could be found for 2011). Typically, there are three full paper and two short paper candidates per year[8]. Exceptions are 2013 with only two full papers and 2010 without any short papers. The corpus contains 32 documents: 20 full papers (7.9% of 253 full papers since 2007) and 12 short papers[9].

[7] https://agile-online.org/index.php/conference/springer-series
[8] https://agile-online.org/index.php/conference/proceedings
[9] Full number of short papers cannot be derived automatically, see supplemental material.

Table 1. Reproducibility-related keywords in the corpus, ordered by sum of matches per paper

citation	reproduc..	replic..	repeatab..	code	software	algorithm(s)	(pre)process..	data	result(s)	all
Foerster et al. (2012)	0	0	0	2	3	11	140	129	41	326
Wiemann & Bernard (2014)	0	0	0	0	0	0	20	98	3	123
Mazimpaka & Timpf (2015)	0	0	0	3	0	4	4	97	10	118
Steuer et al. (2015)	0	0	0	0	0	25	12	64	17	118
Schäffer et al. (2010)	0	0	0	0	10	1	26	65	6	108
Rosser et al. (2016)	0	0	0	0	2	1	42	51	6	105
Gröchening et al. (2014)	0	0	0	0	0	3	2	69	27	101
Almer et al. (2016)	0	0	0	1	1	1	22	53	22	100
Magalhães et al. (2012)	0	0	0	2	1	20	52	9	1	85
Juhász & Hochmair (2016)	0	0	0	0	1	1	2	55	11	70
Wiemann (2016)	0	0	0	0	3	0	8	55	1	69
Fan et al. (2014)	0	0	0	0	0	3	8	44	12	67
Merki & Laube (2012)	0	0	0	0	0	9	6	40	6	62
Zhu et al. (2017)	2	2	0	2	0	10	7	32	6	61
Kuhn & Ballatore (2015)	0	0	1	2	14	1	5	26	8	58
Soleymani et al. (2014)	1	0	0	0	0	0	4	39	9	56
Fogliaroni & Hobel (2015)	0	0	0	0	0	3	14	30	5	52
Osaragi & Hoshino (2012)	0	0	0	0	0	0	5	36	7	48
Stein & Schlieder (2013)	0	0	0	0	0	0	3	42	3	48
Körner et al. (2010)	0	0	0	0	0	6	5	30	4	45
Knoth et al. (2017)	0	0	0	3	2	1	6	25	7	44
Raubal & Winter (2010)	0	0	0	1	1	1	18	0	13	34
Konkol et al. (2017)	1	0	0	3	1	1	2	4	19	31
Kiefer et al. (2012)	1	0	0	0	2	1	9	10	8	31
Haumann et al. (2017)	0	0	0	0	0	6	8	10	2	26
Josselin et al. (2016)	0	0	0	0	2	1	9	5	8	25
Heinz & Schlieder (2015)	1	0	0	2	1	3	2	14	2	25
Osaragi & Tsuda (2013)	0	0	0	1	1	0	3	16	2	23
Baglatzi & Kuhn (2013)	1	0	0	0	0	0	6	12	3	22
Scheider et al. (2014)	0	0	0	0	1	0	0	13	4	19
Brinkhoff (2017)	0	0	0	0	1	9	2	3	2	17
Schwering et al. (2013)	0	0	0	0	0	4	2	3	5	14
Total	7	2	1	22	47	126	454	1179	280	2131

An exploratory text analysis of the paper corpus investigates the occurrence of keywords related to reproducibility, data, and software. The code is published as an executable document in R Markdown[10] (see supplemental material).

Most frequent terms mentioned are illustrated by Figure 1 and Table 1 shows keyword occurrence per paper and in the entire corpus (bottom row ”Total”). Keyword identification uses word stems, e.g. `reproduc` includes reproducible, reproduce and reproduction. Few papers mention reproducibility, some mention code and software, and many mention processes, algorithms, and data. This points to data and analysis being generally discussed in the publications, while their reproducibility is not deliberated.

3.4 Criteria for Assessing Reproducibility

In this section, we address RQ 2 and define criteria for assessing the reproducibility of GIScience research articles. We build on the recommendations from Section 3.2 and differentiate data, methods, and results as separate dimensions with concrete levels. These address specifics of GIScience research and allow a fine-grained assessment of reproducibility.

[10]http://rmarkdown.rstudio.com/

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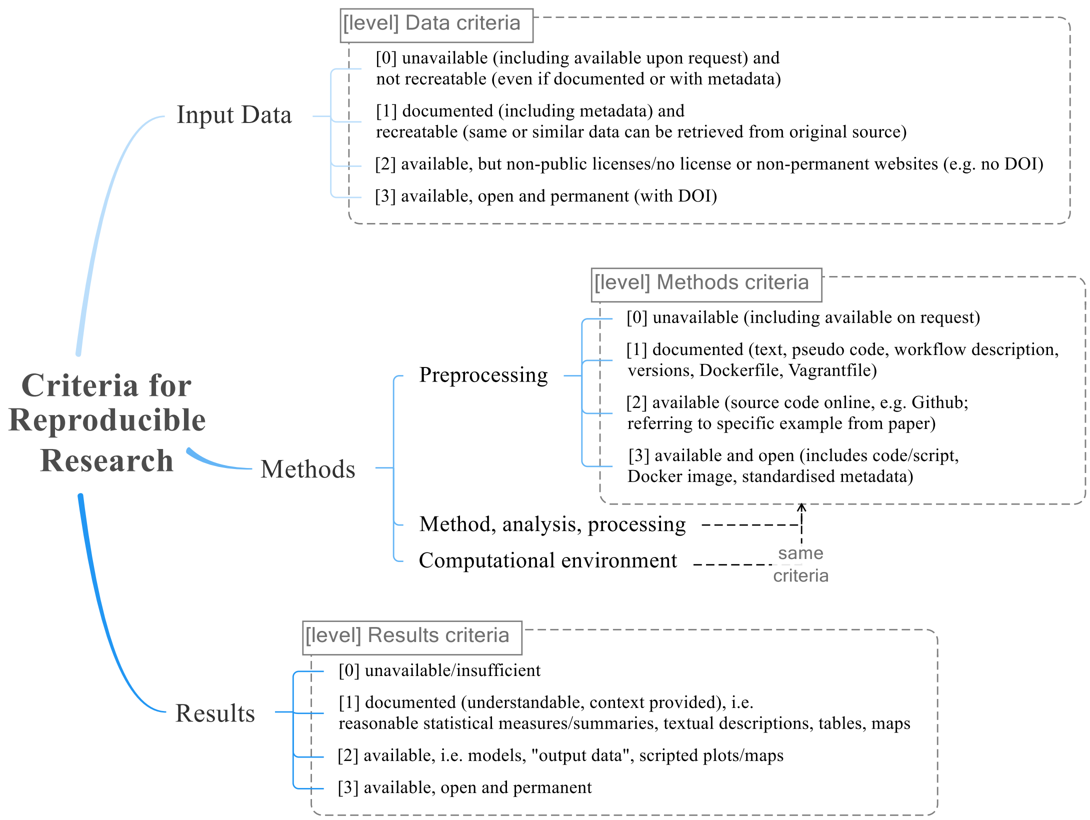

Figure 2. The final reproducible research criteria used for the evaluation. The categories *data*, *methods* (sub-categories: preprocessing, method/analysis/processing, and computational environment), and *results* each have four levels ranging from `0` = unavailable to `3` = fully reproducible
.

The assessed papers showed great variation. Data varies from spatial data to qualitative results from surveys. Methods have an especially wide range from the application of spatial analysis operations to statistical approaches or simulations. Therefore, we split methods up into three sub-criteria addressing the distinct phases and respective software tools: data preprocessing, methods and workflows, and computational environment. Results are maps, formulas, models or diagrams.

Figure 2 shows the criteria and their levels, which range from not applicable (`NA`) via no (value of `0`) to full (`3`) reproducibility. The latter requires the publication to have permanent links to open repositories containing data, relevant elements of methods and workflows (such as software versions, hardware specifications, scripts), and all results. The intermediate levels (`1` and `2`) allow a differentiated evaluation, e.g. for data: at level `1` it is not accessible but documented sufficiently, so others can recreate it; at level `2` it is available yet in a non-persistent way or with a restrictive license.

On purpose, our criteria cannot be applied to conceptual research publications, i.e. without data or code. Their evaluation is covered by an editorial peer review process (see for example Ferreira et al. (2016) for history and future of peer review), and assessing the merit of an argument is beyond the scope of this work.

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Table 2. Survey questions (except for paper identification questions; for full questionnaire see supplemental material)

Question	Possible answers
1. Have you considered the reproducibility of research published in your nominated paper?	• Yes, it is important to me that my research is fully reproducible • Yes, I have somewhat considered reproducibility • No, I was not concerned with it • Other (please add)
2. Do you agree with our rating of your publication? Please comment.	*Open answer*
3a. Please rate how strongly the following circumstances have hindered you from providing all data, methods and results used/developed during your research?	• The need to invest more time into the publication • Lack of knowledge how to include data/methods/results into the publication • Lack of tools that would help to attach data/methods/results to the publication • Lack of motivation or incentive • Legal restrictions Available ratings: • Not at all • Slightly hindered • Moderately hindered • Strongly hindered • Main reason
3b. Please add here if there were any other hindering circumstances	*Open answer*
4. What would you suggest to AGILE community to encourage publishing fully reproducible papers?	*Open answer*

3.5 Survey: Author Feedback on Assessment of Reproducibility

To understand better the reasons behind the low scores and to give the authors an opportunity to respond, we conducted a survey among authors using Google Forms[11] (see Table 2, cf. Baker (2016a) for a large scale survey on the topic). The full survey and responses are included in the supplemental material. The survey was sent to authors via e-mail and was open from 23 October to 24 November 2017. In case of obsolete e-mail addresses, we searched updated ones and resent the form. Out of a total of 82 authors, 22 filled in the survey resulting in responses for 17 papers, because six participants did not give consent to use their answers, two authors participated twice for different papers, and some papers had more than one individual response.

[11] https://www.google.com/forms/about/

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Table 3. Reproducibility levels for paper corpus; '-' is category not available

author	short paper	input data	preprocessing	method/analysis/processing	computational environment	results
Zhu et al. (2017)		0	1	1	1	1
Knoth et al. (2017)		0	-	0	1	1
Konkol et al. (2017)		2	2	1	1	1
Haumann et al. (2017)	X	0	1	1	0	1
Brinkhoff (2017)	X	0	-	1	0	0
Almer et al. (2016)		0	-	1	1	1
Wiemann (2016)		2	-	1	1	1
Juhász & Hochmair (2016)		0	1	1	0	0
Josselin et al. (2016)	X	1	-	0	0	1
Rosser et al. (2016)	X	0	-	1	0	0
Kuhn & Ballatore (2015)		-	-	-	-	-
Mazimpaka & Timpf (2015)		2	1	1	1	1
Steuer et al. (2015)		2	0	1	1	1
Fogliaroni & Hobel (2015)	X	-	-	-	-	-
Heinz & Schlieder (2015)	X	0	0	1	1	1
Scheider et al. (2014)		1	1	2	1	1
Gröchening et al. (2014)		2	0	1	0	1
Fan et al. (2014)		0	1	1	0	1
Soleymani et al. (2014)	X	0	0	1	0	0
Wiemann & Bernard (2014)	X	0	0	1	0	0
Osaragi & Tsuda (2013)		0	1	1	0	1
Baglatzi & Kuhn (2013)		-	-	-	-	-
Li et al. (2013)	X	0	0	1	-	1
Stein & Schlieder (2013)	X	0	-	1	0	1
Osaragi & Hoshino (2012)		0	0	1	0	1
Magalhães et al. (2012)		0	0	1	0	0
Foerster et al. (2012)		1	-	1	1	1
Merki & Laube (2012)	X	0	-	1	1	1
Kiefer et al. (2012)	X	0	1	1	0	1
Raubal & Winter (2010)		-	-	-	-	-
Schäffer et al. (2010)		0	0	1	1	1
Körner et al. (2010)		-	-	-	-	-

4 RESULTS

4.1 Reproducibility Assessment of Paper Corpus

To address RQ 3, we reviewed the papers in the corpus with the introduced criteria. Our objective in publishing the full evaluation results is not to criticise or rank individual papers, but to identify the current overall state of reproducibility in GIScience research in a reproducible manner. The scientific merit of all papers was already proven by their nomination for the best paper award.

Evaluators chose to review papers without conflict of interest until two reviewers from different research groups were assigned per paper. A general guideline was to apply the lower of two possible levels in cases of doubt, such as partial fulfilment of a criterion or disagreement between the evaluators. The assessment focuses on algorithmic and data-driven research papers. Thus, 5 fully conceptual papers were not assessed, while 15 partly conceptual ones were included. Notably the data preprocessing criterion did not apply to 14 research papers. Table 3 shows the assessment's results.

Figure 3 shows the distribution of reproducibility levels for each criterion. None of the papers reaches the highest level of reproducibility in any category. Only five papers reach level 2 in the data criterion, which is still the highest number of that level across all categories. Especially

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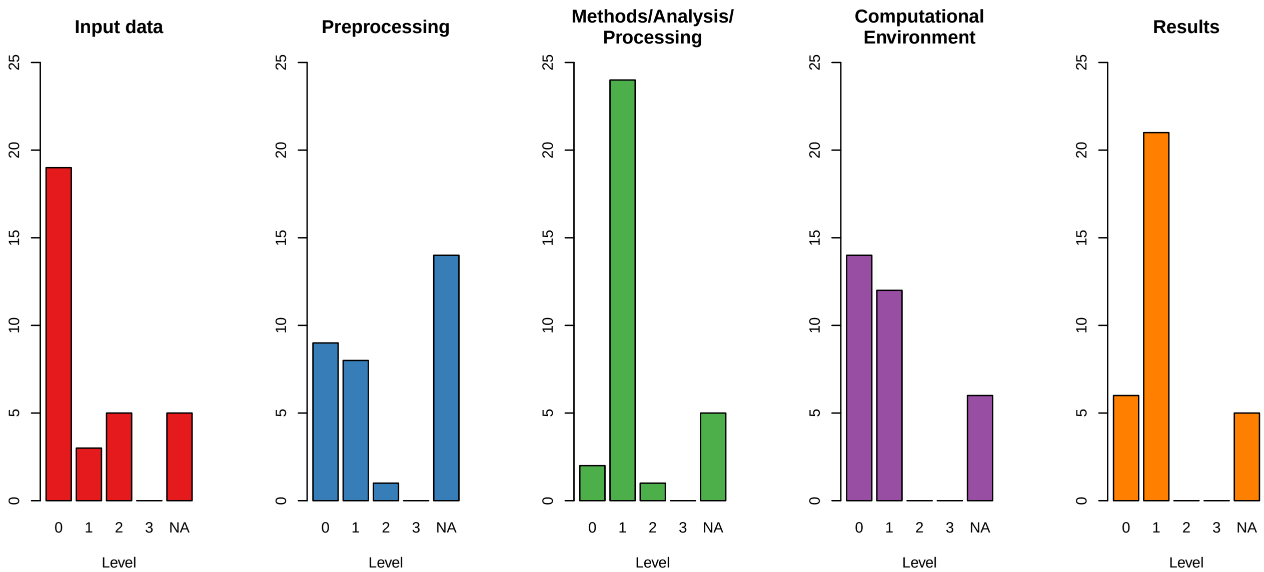

Figure 3. Results of reproducibility assessment: level of reproducibility ranges from `0` (not reproducible) to `3` (fully reproducible); `NA`s include 5 conceptual papers (all categories are `NA`)

problematic is the high number (19 papers) with level `0` for data, meaning that the specific data is not only unavailable but it is not re-createable from the information in the paper. Data preprocessing applies to 18 publications and the levels are low. Only one publication has level `2`. Concerning the methods and results criteria, 19 out of 32 papers have level `1` in both, meaning an understandable documentation is provided in the text.

Figure 4 shows average reproducibility levels are low and do not change significantly over time, with the average being below level `1` for all categories. Tables 4 and 5 contain summary statistics per criterion and means[12] for full and short papers. For each criterion, full papers reach higher levels than short papers (see Table 5).

Table 4. Statistics of reproducibility levels per criterion

	input data	preproc.	method/analysis/proc.	comp. env.	results
Min.	0.00	0.00	0.00	0.00	0.00
Median	0.00	0.50	1.00	0.00	1.00
Mean	0.48	0.56	0.96	0.46	0.78
Max.	2.00	2.00	2.00	1.00	1.00
NA's	5.00	14.00	5.00	6.00	5.00

Table 5. Mean levels per criterion for full and short papers

	input data	preproc.	method/analysis/proc.	comp. env.	results
Full papers	0.75	0.67	1.00	0.62	0.88
Short papers	0.09	0.33	0.91	0.20	0.64

[12]The few data points and categorical variable type require cautious interpretation of the mean.

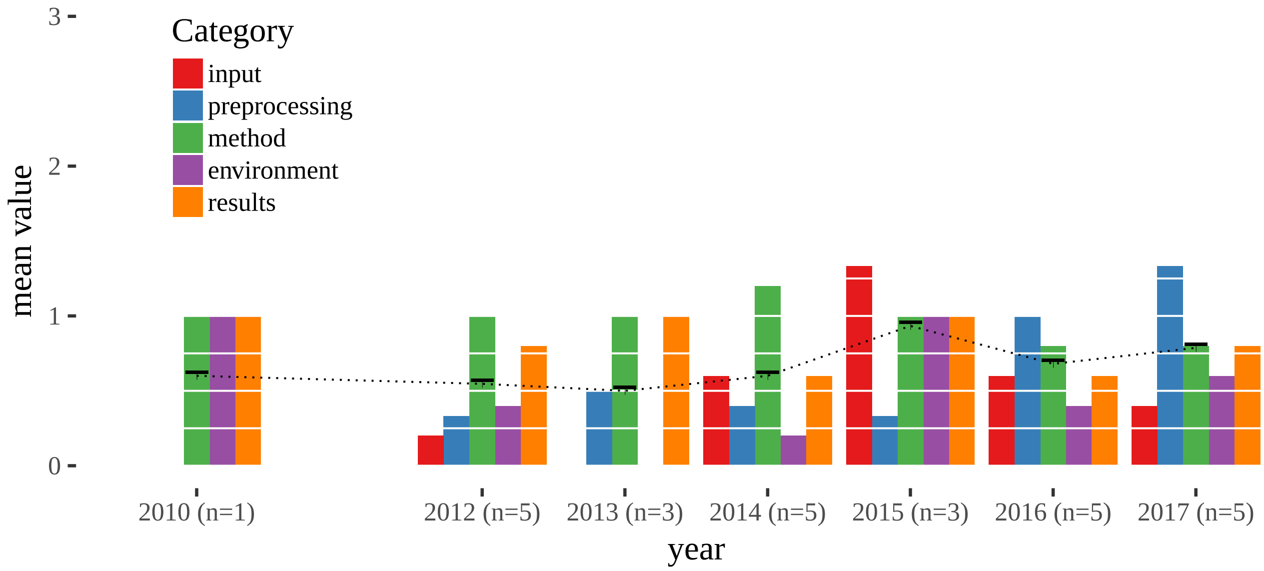

Figure 4. Mean reproducibility levels per category over time; black dotted line connects the mean per year over all categories (in 2010 only one of three papers could be assessed, reaching level 1 for methods)

4.2 Survey Results

Authors were asked to comment on their agreement or disagreement with our evaluations of their specific paper. Seven responses fully agreed with the evaluation, five agreed partly, two expressed disagreement, and one did not answer the question. Most disagreement addresses the definition of criteria. Multiple authors argued that such requirements should not be applicable for short papers, and that specific data is not always necessary for reproducibility. Others disagreed on treating "availability upon request" as "unavailable". One argued that OpenStreetMap data is by default "open and permanent", while our criteria miss direct links to specific versioned subsets of data.

The answers suggest that authors are generally aware of the need of reproducibility and in principle know how to improve it in their work. However, many do not consider it a priority, giving as reasons the lack of motivation (eight respondents) or the required extra efforts. They say these are disproportionately large in comparison to the added value.

According to the survey results, reproducibility was important to more than half of the respondents (see Figure 5). Only two respondents claim they were not at all concerned about it (both short papers). Further comments revealed some authors consider short papers as introductions of new concepts and generally too short for reproducibility concerns. The paper corpus supports this opinion because short papers reach overall lower levels.

In contrast, we argue that transparency should depend on the publication type but is a feature of the entire scientific process. Especially at early stages, the potential for external review and collaboration can be beneficial for authors. Further, putting supplementary materials in online repositories addresses the problem of word count limits (for full and short papers) that many authors struggle with.

To identify barriers to reproducibility, the authors were asked to rate how strongly five predefined barriers (Table 2) impacted their work's reproducibility. They could also add their own reasons, for which they mentioned limited length of paper, and required additional financial resources. Table 6

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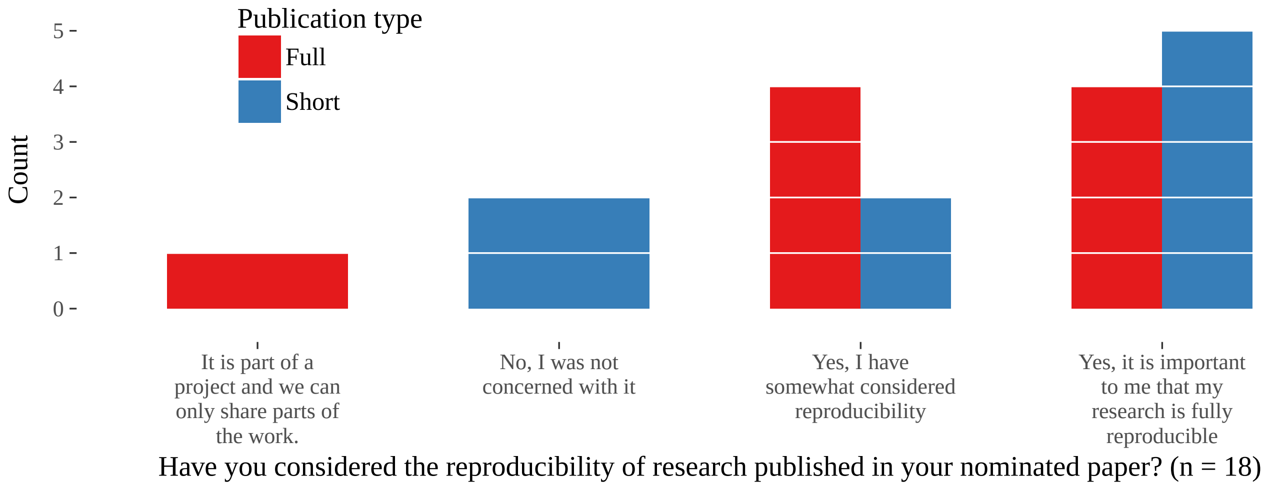

Figure 5. Author survey results on the importance of reproducibility

shows legal restrictions and lack of time were mentioned most frequently, with only one respondent indicating that they played no role. Although lack of knowledge on how to include data, methods and results was not considered by many as a barrier, several respondents noted a lack of supporting tools as main impediment for reproducibility.

Respondents also shared their ideas for encouraging reproducibility of AGILE publications. Four suggested Open Access publishing and asked for solutions for sensitive data. A few suggested encouraging and promoting collaboration across research institutes and countries to mitigate ephemeral storage and organisations. Some respondents proposed an award for reproducible papers, requiring reproducibility for the best paper nomination, or conference fee waivers for reproducible papers. In summary, almost all authors agreed on the importance of the topic and its relevance for AGILE.

4.3 A critical review of this paper's reproducibility

We acknowledge this paper has its own shortcomings with respect to reproducibility. The *input data* (i.e. the paper corpus) for the text analysis cannot be re-published due to copyright restrictions. Our sample is biased (although probably positively) as we only considered award nominees. Access to all papers would have allowed a random sample from the population. Regarding the *methodology*, the created criteria and their assignment by humans cannot honour all details and variety of individual research contributions and is inherently subjective. We tried to mitigate this by applying a four eyes principle, and transparently sharing internal comments and discussion on the matter in the supplemental material. The material comprises an anonymised table with the survey results and a literate programming document, which combines data preprocessing, analysis, and visualisations. Using our own classification, we critically assign ourselves level `0` for data and target level `3` for methods and results.

5 DISCUSSION & CONCLUSIONS

5.1 Improving day-to-day Research in GIScience

Our evaluation clearly identifies issues of reproducibility in GIScience. Many of the evaluated papers use data and computer-based analysis. All have been nominated for the best paper award within a double-blind peer review and represent the upper end of the quality spectrum at an established

Table 6. Hindering circumstances for reproducibility for each survey response (n = 17)

Legal restrictions	Lack of time	Lack of tools	Lack of knowledge	Lack of incentive
Main reason	Strongly hindered	Not at all	Not at all	Strongly hindered
Main reason	Not at all	Not at all	Not at all	Moderately hindered
Main reason	Slightly hindered	Strongly hindered	Moderately hindered	Strongly hindered
Main reason	Not at all	Slightly hindered	Not at all	Not at all
Strongly hindered	Strongly hindered	Strongly hindered	Moderately hindered	Strongly hindered
Moderately hindered	Main reason	Not at all	Not at all	Not at all
Slightly hindered	Moderately hindered	Slightly hindered	Slightly hindered	Moderately hindered
Slightly hindered	Not at all	Main reason	Strongly hindered	Not at all
Not at all	Moderately hindered	Not at all	Moderately hindered	Not at all
Not at all	Strongly hindered	Strongly hindered	Strongly hindered	Slightly hindered
Not at all	Moderately hindered	Not at all	Not at all	Not at all
Not at all	Slightly hindered	Main reason	Not at all	Strongly hindered
Not at all	Main reason	Not at all	Not at all	Not at all
Not at all	Main reason	Not at all	Not at all	Not at all
Not at all	Moderately hindered	Moderately hindered	Not at all	Strongly hindered
Not at all	Not at all	Not at all	Not at all	Not at all
Not at all	Slightly hindered	Not at all	Slightly hindered	Not at all

conference. Yet overall reproducibility is low and no positive trend is perceivable. It seems current practises in scientific publications lack full access to data and code. Instead only methods and results are documented in writing.

A lasting impact on the reproducibility of research requires changes in educational curricula, lab processes, universities, journal publishing, and funding agencies ("Reproducible Research" 2010; McKiernan, 2017) as well as reward mechanisms that go beyond paper citations (cf. term "altmetrics" in Priem et al., 2010). This is a major and long-term endeavour. Here, we focus on recommendations and suggestions for individual researchers and a specific organisation: AGILE. A snowball effect may lead to a change in practises in the GIScience community. The remainder of this paper addresses RQ 4 by formulating suggestions to researchers and the AGILE conference organisers.

5.2 Suggestions to Authors

Regarding habits and workflows, the Carpentries (the union[13] of Data Carpentry (Teal et al., 2015) and Software Carpentry (Wilson, 2006)) offer lessons on tools to support research, such as programming and data management, across disciplines. Further resources are available from programming language and software communities, research domains, and online universities. Often these are for free because the software is Free and Open Source Software (FOSS) and driven by a mixed community of users and developers. Ultimately, proprietary software is a deal-breaker for reproducibility (cf. Ince, Hatton, and Graham-Cumming, 2012; Baker, 2016b). OSGeo-Live[14] provides a simple environment to test open alternatives from the geospatial domain, and several

[13] http://www.datacarpentry.org/blog/merger/
[14] https://live.osgeo.org/

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websites offer help in finding FOSS comparable to commercial products[15]. But it is not only about the software. It can be as simple as "naming things" sensibly[16], as realistic as not striving for perfection but following "Good enough practices in scientific computing" (Wilson et al., 2017), as egoistic as "selfish reasons to work reproducibly" (Markowetz, 2015), and as FAIR[17] as "structuring supplemental material" (Greenbaum et al., 2017).

5.3 Recommendations to Conferences in GIScience and Organisations like AGILE

What can conferences and scientific associations do to encourage reproducibility? The crucial step is acknowledging the important role organisations like AGILE can play in the adoption of reproducible research practises, building upon a large body of guidelines, documentation and software. In the remainder of this section we propose concrete actions using AGILE as the leading example.

Recognising the importance of reproducibility could take the form of an **award for reproducible papers**. This is already done by other communities, e.g. the ACM SIGMOD 2017 Most Reproducible Paper Award[18]. At AGILE reviewers suggest submissions to be nominated for best (short) papers and could also briefly check for reproducibility. A detailed reproduction could be the responsibility of a new Scientific Reproducibility Committee led by a Reproducibility Chair, working alongside the existing committees and their chairs. Committee membership would be publicly recognised. The "most reproducible paper" could be prominently presented in the conference's closing session.

Kidwell et al. (2016) demonstrate open data **badges** had a positive effect on actual publishing of data in the journal Psychological Science. They use badges and corresponding criteria by the Center for Open Science[19] (COS). Further examples are the "kite marks" by the journal Biostatistics (Peng, 2011), the Association for Computing Machinery's (ACM) common standards and terms for artifacts[20], and the Graphics Replicability Stamp Initiative (GRSI)[21]. While AGILE could invent own badges, re-using existing approaches has practical (no need to design new badges), organisational (no need to reinvent criteria), and marketing (higher memorability) advantages. Author guidelines would include instructions on how to receive badges for a submission. The evaluation of badge criteria would be integrated in the review and could inform the reproducible paper award.

Author guidelines are the essential means to set the scene for a reproducible conference[22]. Independently of advertising awards and badges, they should include clear guidelines on when, how, and where to publish supplemental material (data, code). Authors must be made aware to highlight reproducibility-related information for reviewers and readers with *author guidelines for computational research*. These should comprise practical advice, such as code and data licenses[23], and instructions on how to work reproducibly, e.g. in form of a space for sharing tools and data, which is the most popular suggestion from the survey (seven respondents).

While the established peer-review process works well for conceptual papers, an extra **track or**

[15] E.g. https://opensource.com/alternatives or https://alternativeto.net

[16] https://speakerdeck.com/jennybc/how-to-name-files by Jennifer Bryan

[17] Force11.org. Guiding principles for findable, accessible, interoperable and re-usable data publishing: version B1.0. https://www.force11.org/node/6062

[18] http://db-reproducibility.seas.harvard.edu/ and https://sigmod.org/2017-reproducibility-award/

[19] https://osf.io/tvyxz/wiki/home/

[20] https://www.acm.org/publications/policies/artifact-review-badging

[21] http://www.replicabilitystamp.org/

[22] Cf. SIGMOD 2018 CFP, https://sigmod2018.org/calls_papers_sigmod_research.shtml

[23] E.g. OSI compliant for code and Open Definition compliant for data, see http://licenses.opendefinition.org/

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submission type[24] allows a special process (e.g. public peer review) and can accommodate submissions focussing on reproducibility without an original scientific contribution. Such publications can include different authors, e.g. technical staff, or even reviewers as practised by Elsevier's Information Systems journal. They also mitigate limitations on research paper lengths. Unfortunately, they can also convey the counterproductive message of reproducibility being cumbersome and uncommon.

Such a special track as well as the regular conference proceedings should be published as **Open Access**[25] in the future. It might even be possible to re-publish short papers and abstracts of previous conferences after solving juridical concerns (e.g. if author consent is required). AGILE could utilise existing repositories or operate its own. Using third party repositories[26] for supplements, reduces the burden on the AGILE organisation. Choosing **one repository** allows collecting all AGILE submissions under one tag or community[27]. An AGILE-specific repository allows more control yet requires more work and might have lower visibility, since the large repositories are well indexed by search engines. Both approaches can support a double-blind review by providing anonymous view-only copies of supplemental material[28].

What skills related to reproducibility are desirable for authors at the 30th AGILE conference? Predicting 10 years ahead might not be scientific, but it allows formulating a vision. We assume there will be hardly any paper not utilising digital methods, such as software for analysis, interactive visualisations, or open data. Ever more academics will meet a competitive selection process, where quality of research will be measured by its transparency and novelty. To achieve novelty in a setting where all research is saved, findable and potentially interpreted by artificial intelligence (N. Jones, 2016), a new contribution must be traceable. Thus, the trend towards Open Science will be reinforced until using and publishing open source code and open data as well as alternative metrics beyond citations will be natural. As of now, AGILE is not ready for such research. It has identifiers (DOIs) only for full publications and lacks open licenses for posters and (short) papers. Statements on preprints (publication before submission) and postprints ("green" Open Access[25]) are missing.

We see AGILE, carried by its member labs and mission[29], in a unique position to establish a common understanding and practise of reproducible research. Firstly, member labs can influence education, especially at graduate level, and ideally collaborate on **open educational material**. Completing a Ph.D. in an AGILE member lab and participating in AGILE conferences should qualify early career scientists to publish and review reproducible scholarly works. Secondly, the conference can take a leading role to set up new norms for conference review and publication but at the same time cooperate with other conferences (e.g. ACM SIGMOD). At first AGILE would encourage but eventually demand the highest level of reproducibility for all submissions. This process certainly will take several years to complete.

[24] See IEEE's CiSE magazine's Reproducible Research Track https://www.computer.org/cise/2017/07/26/reproducible-research-track-call-for-papers/, and Elsevier journal Information Systems' section for invited reproducibility papers, https://www.elsevier.com/journals/information-systems/0306-4379/guide-for-authors

[25] See https://open-access.net/DE-EN/information-on-open-access/open-access-strategies/

[26] Beside the incumbents Figshare (https://figshare.com/), Open Science Framework (OSF) (https://osf.io/, community-driven) and Zenodo (https://zenodo.org/, potentially preferable given AGILE's origin because it is funded by EU), a large number of Open Access repositories exists, see http://roar.eprints.org/ and http://opendoar.org/, including platforms by publishers, e.g. Springer (https://www.springer.com/gp/open-access), or independent organisations, e.g. LIPIcs proceedings (https://www.dagstuhl.de/en/publications/lipics).

[27] Cf. http://help.osf.io/m/sharing/l/524053-tags and https://zenodo.org/communities/

[28] See http://help.osf.io/m/links_forks/l/524049-create-a-view-only-link-for-a-project

[29] https://agile-online.org/index.php/about-agile

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Researchers will have to leave their comfort zone and change the way they work. They also have to see benefits immediately to overcome old habits (Wilson et al., 2017). The evidence for benefits of Open Science are strong (McKiernan et al., 2016), but to succeed the community must embrace the idea of a reproducible conference. We acknowledge that fully reproducible GIScience papers are no small step for both authors and reviewers, but making them the standard would certainly be a giant leap for AGILE conferences. We are convinced AGILE can provide the required critical mass and openness and hope the experiences and information in this work contribute a starting point.

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