State of the Practice for GIS Software

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Abstract

We present a reproducible method to analyze the state of software development practices in a given scientific domain and apply this method to Geographic Information Systems (GIS). The analysis is based on grading a set of 30 GIS products using a template of 56 questions based on 13 software qualities. The products range in scope and purpose from a complete desktop GIS systems, to stand-alone tools, to programming libraries/packages. The final ranking of the products is determined using the Analytic Hierarchy Process (AHP), a multicriteria decision making method that focuses on relative comparisons between products, rather than directly measuring qualities. The results reveal concerns regarding the correctness, maintainability, transparency and reproducibility of some GIS software. Three recommendations are presented as feedback to the GIS community: i) Ensure each project has a requirements specification document; ii) Provide a wealth of support methods, such as an IRC (Internet Relay Chat) channel, a Stack Exchange tag for new questions, or opening the issue tracker for support requests, as well as the more traditional email-based methods; and, iii) Design product websites for maximum transparency (of the development process); for open source projects, provide a developer’s guide.

Keywords:
Geographic Information Systems, scientific computing, software engineering, software quality, review, Analytic Hierarchy Process

1. Introduction

This paper analyzes the state of development practice in Geographic Information Systems (GIS). The scope and purpose of the software analyzed ranges from complete desktop GIS systems, to stand-alone products, to programming libraries. GIS software requires sophisticated data structures and image processing algorithms. The complexity of GIS software raises concerns for software qualities such as correctness, reliability and performance. To address these concerns, and produce high quality software, requires solid Software Engineering (SE) and Scientific Computing (SC) development practices.

The authors of this paper are not GIS experts; however, we are experts in SE applied to scientific computation software. As outsiders, we can claim objectivity, since we have no prior attachment to any of the software examined in this paper. We hope to provide valuable feedback to the GIS community to help improve the quality of their software.

We arrive at our feedback and conclusions through a reproducible process of systematically grading software products in the GIS domain based on 13 software qualities. We do not grade the products on functionality. Rather, we grade the development process of the projects, and
determine how well the projects adhere to SE principles and practices. A main goal of the software grading process is objectivity, and quantification, wherever possible. An external list of software products written by a domain expert acts as an authoritative list of software to be graded. As a part of the grading, we perform a pairwise comparison between each of the software products using a multicriteria decision analysis process. Based on the rankings from the decision analysis, we then analyze trends between software products.

Our inspiration for this project comes from Gewaltig and Cannon (2012), and the later paper, Gewaltig and Cannon (2014). (Our work is based mainly on the earlier version, since the classification system in that paper is the simpler of the two, and it still fulfills our needs). In their papers, Gewaltig and Cannon perform a software review in the domain of computational neuroscience. We build and expand on their process, as we previously did for mesh generation software (Smith et al., 2016) and for seismology software (Smith et al., 2017). Gewaltig and Cannon’s review gathers data from the public information on the software product’s website and analyzes it for trends to build feedback. The authors conclude that there is often a misunderstanding between developers and users regarding the reasons for creating the software and expectations for its features. Much of the software examined was written by students during their Master’s or PhD research; many of the developers did not have backgrounds in computer science or SE. Their priority was their scientific application, not best practices in SC. (Segal, 2007) refers to this category of developers as professional end user developers. This type of developer seems common for SC software.

One major problem with scientific software development is a communication barrier between scientists and software engineers when discussing requirements. The barrier exists because the scientists have experience in their field, but less with software development. The scientists know that the requirements will change, but they cannot precisely convey how they will evolve. Not correctly articulating requirements, or changing requirements midway through a project, greatly impacts the productivity of the development team (Segal, 2005). When engineers create the software, the resulting development artifacts, such as user manuals and introductory examples, are not sufficient for the scientists to understand the product (Segal, 2008). When end users (scientists) develop the software product, the situation is not improved, since their training in science has not prepared them to consider important software qualities, like maintainability and reusability. The differences between SE and SC has led to a chasm between these two disciples (Kelly, 2007).

The remainder of this article is organized as follows: Section 2 provides background information and outlines previous work. Our methods are explained in Section 3. A summary of our results is presented in Section 4 and our recommendations are detailed in Section 5. Concluding thoughts are found in Section 6.

2. Background

The definitions found in this section include the software qualities and SC best practices that our software grading template is based on. Also included is a quick overview of the Analytic Hierarchy Process (AHP), a multicriteria decision making method that we use to analyze the results of the software grading.

2.1. Software Qualities

Our analysis is built around a set of software qualities. Software qualities can be internal, in which case the qualities only concern developers, or external, in which case the qualities are visible to the end users (Ghezzi et al., 2002, p. 16). Strong internal software qualities help
achieve strong external qualities. Qualities not only concern the software product itself, but also the process used, and the artifacts generated (Ghezzi et al., 2002, p. 16–17). Artifacts include documentation and test data, which are created to improve and measure the software’s quality.

This paper measures 13 software qualities, as summarized in Smith et al. (2016): installability, correctness and verifiability (measured together), reliability, robustness, performance, usability, maintainability, reusability, portability, understandability, interoperability, visibility and reproducibility. The majority of the above qualities of software come from Ghezzi et al. (2002). We have excluded qualities that we would not be able to sufficiently measure, such as productivity and timeliness. We have also added two qualities that we believe are important to the overall quality of SC software: installability and reproducibility.

The above software qualities come from SE, and apply to any class of software. Specific SC software development principles are also important to consider when examining GIS software. The “best practices” (Wilson et al., 2013) for SC form a checklist of eight basic practices that promote reliable and maintainable code. We use the key ideas from this checklist for creating our grading template. For example, from this list we draw our standards for source code documentation, reuse of libraries, the use of an issue tracker and other key elements of correctness and maintainability.

2.2. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a multicriteria decision making process. The objective of AHP is to compare multiple results based on multiple criteria important to the decision (Saaty, 1990). In this paper, AHP is used in part to compare qualities of software between each other. Since there is no formal scale or units in which these qualities are measured, we use AHP to remove this problem and focus on relative and pairwise comparisons. AHP consists of a set of n options and a set of m criteria with which the options are graded. The criteria are prioritized. Then, for each of the criterion, a pairwise analysis is performed on each of the options, in the form of an nxn matrix a. The value of \( a_{jk} \) ranges from 1, when options j and k are equally graded, to 9, when option j grades extremely (maximally) higher than k. The definitions of the values between 1 and 9 are found in Saaty (1990).

The value of \( a_{kj} \) is the inverse of \( a_{jk} \) (\( a_{kj} = 1/a_{jk} \)). Once the matrix a has been filled, weights are generated by creating a new matrix b. Entry \( b_{jk} = a_{jk}/\sum(a_k) \), where the dot (·) indicates the entire row. Next, these weights are averaged to determine the overall score for that option and criterion. All of the scores are weighted according to the priorities of the criteria. Final scores are generated to create a ranking for each of the options. These final scores give a high-level view of how an option compares to the others based on all criteria (Mocenni, 2014).

In our project, the n graded software products are the options. The 13 software qualities are the m criteria. In Triantaphyllou and Mann (1995) the authors warn that options’ final scores should not be considered as absolute ranks. In our experiment, we certainly do not wish to absolutely rank software products, but more to sort the software products into groups based on their software qualities.

3. Methods

In this paper, we create a systematic grading and analysis procedure for a list of SC software products, in particular GIS software. First, the software is graded, based on the software qualities and best practices of SC software from Section 2. Second, the results are discussed and analyzed for trends.
3.1. Software Product Selection

To select the software for analysis, we followed John W. Wilson’s list of “Useful remote sensing software” (Wilson [2014]). The list provides a comprehensive list of GIS software, and libraries. Most of the software is free and open source, with contributions from both researchers and independent developers. Not all of the links to software products in Wilson’s list were used. For example, links to the Python programming language and the R project for statistical computing, were removed because these are general programming languages, and thus not specific to GIS. Additionally, the links to sample data sets and tutorial web pages were not considered, since they are not software products. The full list of software graded can be found in Section 4. In total, there are 30 software products on the list.

3.2. Grading Template

The template we used for grading the software products is a collection of 56 questions. The full list is available in the Appendix and at https://data.mendeley.com/datasets/6kprpvvv7r7/1. The questions are divided into the 13 software qualities listed in Section 2.1. Due to the qualitative or subjective nature of some of the software qualities (e.g. reliability, robustness), the template had to be carefully structured. When choosing questions (measures), we aimed for unambiguity, and quantification where ever possible (e.g. yes/no answers). As outsiders, we looked for measures that are visible, measurable and feasible in a short time with limited domain knowledge. Unlike a comprehensive software review, this template does not grade on functionality and features. Therefore, it is possible that a relatively featureless product can outscore a feature-rich product.

In the first section of the template, general information is gathered about the software. This information contains the software name, URL, license information, possible educational backing, funding methods, and the dates for when the project was released and when it was last updated. A project is defined as alive if it has been updated within the last 18 months, and dead otherwise. This time frame is arbitrary, but it seems appropriate since this includes the usual time frame for new operating system updates and more than a full calendar year for educational institutions. As per Gewaltig and Cannon (2012), we define the category of public software as software intended for use by the public. Private (or group) software is only aimed at a specific group of people. Lastly, concept software is available simply to demonstrate algorithms or concepts, and not for use in a production setting. The main categories of development models are: open source, where source code is freely available under an open source license; freeware, where a binary or executable is provided for free; and, commercial, where the user must pay for the software product. If the product is open source, we note the programming language used.

We use a virtual machine to provide an optimal testing environments for each software product. During the process of grading the 30 software products, it is much easier to create a new virtual machine to test the software on, rather than using the host operating system and file system. Adding and removing software from one’s computer can often be difficult; we use virtual machines to avoid this headache. Once grading of a software is complete, the virtual machine with the software on it is destroyed, and the host operating system is oblivious. Virtual machines also provide fresh installs of operating systems, which minimizes or completely removes “works-on-my-computer” errors. Unless the software has dependencies that must be installed, any installation instructions that are provided by the software developers should be compatible with a fresh install of an operating system. In our grading data, we note the details of the virtual machine, including hypervisor and operating system versions.
3.3. Measuring Qualities

For each of the following qualities, the software receives a grade from one to ten. These grades are the grader’s subjective feeling about the software based on the measurements, past experiences and the other GIS software products. The grader must aim for consistency during the grading process. At the end of the ranking process, the potential subjectivity is mitigated by the use of AHP, since in AHP it is the relative difference that matters. As long as two graders are internally consistent, with their grades mostly trending in the same direction, their relative comparisons matrix in AHP should be similar. The objectivity of the grading process is discussed further in Section 3.4.

**Installability** is an aspect of the software that we can thoroughly analyze. To grade qualities such as usability or robustness, we must first install the software. Installation is also the primary entry point for every user of the software: beginner or advanced. We check for the absence or presence of install instructions. These instructions are ideally linear and highly automated, including the installation of any external libraries that need to be installed. Before proceeding, if there is a way to validate the installation, we run the validation. At the end of the installation and testing, and if an uninstallation is available, we run it to see if any problems were caused. The complete grading template for installability is presented in Table 1. A similar set of measures is used for the other quality gradings.

| Installability Measure                                      | Metric                  |
|------------------------------------------------------------|-------------------------|
| Are there installation instructions?                       | yes, no                 |
| Are the installation instructions linear?                  | yes, no                 |
| Is there something in place to automate the installation?   | yes*, no                |
| Is there a specified way to validate the installation, such as a test suite? | yes*, no                |
| How many steps were involved in the installation?          | number                  |
| How many software packages need to be installed?           | number                  |
| Run uninstall, if available. Were any obvious problems caused? | unavail, yes*          |

Table 1: Installability grading template (unavail means that uninstall is not available and a * indicates that the measurement should also be accompanied by explanatory text.)

**Correctness** is difficult to grade because it is an absolute quality. What we are actually measuring is confidence in correctness and the related quality of verifiability. To accurately grade correctness/verifiability, there must be a requirements specification document and the behaviour of the software must strictly adhere to it. We do not have the time or the means to rigorously test every piece of software to this extent. We look for indirect means of judging correctness. For instance, we look for the use of standard libraries, in which the community has confidence, and confidence building techniques, such as such as assertions in the code, and documentation generated from the code.

Since the duration of our usage of the software is quick and structured, we can easily analyze surface reliability. We cannot grade long term reliability of the product, but poor reliability during grading is certainly a cause for concern. We know how the software is expected to behave via the installation guide and tutorial (if present), and we also complete a getting started tutorial, if available. If the software does not behave as expected during this duration of usage, the software is graded poorly with respect to reliability.
When we grade surface robustness, we are trying to break the software. We cannot test all features of a product, and we cannot provide exhaustive cases of garbage input to the software. Purposely making errors during the getting started tutorial and other interactions with the software tests the robustness of the program, and its error handling.

Performance is a very difficult quality of software to measure. For practical reasons, the size of the problems we are testing cannot strain the products. Instead of measuring performance directly we look on the surface for evidence that performance was considered, such as a makefile that shows the presence of a performance profiler.

Surface usability is based on our impressions of the “human-friendliness” of the product during the grading time frame. During our time using the product, we checked for the existence of a getting started tutorial. This tutorial is an explicit guide for first time users that has linear steps for the absolute basic usage of the product. We also look for a more detailed user manual. If any features are hidden or difficult to find, then they do not satisfy Norman’s design principle of visibility (Norman, 2002). We also measure whether the software has the expected “look-and-feel” for products for that platform. User support techniques, such as web forums, are also considered when assessing usability.

Maintainability is one of the more concrete software qualities to grade. Whether or not the developers write a changelog, use an issue tracking tool, or have multiple versions of the software, are all easy things to examine. If the developer gives information on how their code is reviewed, or have specific instructions on how to contribute to the project, this information adds to the maintainability of a product.

Reusability is a strong theme in both SC best practices and in SE in general. In our grading, we note products that are currently being reused or that make reusability simple. Adding plugin or add-on functionality greatly improves reusability, especially when well-documented. Also, in the case of an API (Application Programming Interface), having full, concise documentation available for programmers improves reusability.

Portability is graded based on what platforms the software is advertised to work on, and how the developers handle portability. Using cross-platform code or a cross-platform build system is evidence that portability was considered in the design and development. Any related discussion of portability or build practices is also noted.

For grading understandability, we examined the source code that comes with open source software products. We checked the source code for objective properties, like modularity, consistent indentation and if concise commenting is used. If there exists a coding standard enforced by the project, it helps understandability. We also checked for documentation regarding software design, such as a module guide for the system architecture. If source code is unavailable, the software is not graded on this criterion.

Interoperability grading consists of examining if the product can communicate or otherwise interact with any external systems. We checked for this kind of interaction and whether an external API document is provided.

Transparency is a quality that is ever-present when grading software products. All information we need for grading, including the getting started tutorial and the source code itself all depend on how the information is presented, and how easy it is to find. We are also interested in whether a development process has been defined. For example, a waterfall or a spiral development model could be used, or perhaps a more ad-hoc process has been documented.

Reproducibility measures any evidence or documentation of development or testing platforms. If there are any tools that alleviate inconsistencies between hardware or software platforms, the reproducibility of the software’s results can be tested. As stated above, there are
several reasons we use virtual machines for using software during grading. These reasons are applicable for development as well. Documented methods of development or testing on virtual machines greatly helps reproducibility.

3.4. Approach to Grading

During the grading process, the grader is faced with the task of getting a concise snapshot of each software product, based on one to three hours of interaction. The grader needs a good strategy to approach this task. Each grader may have a strategy that is slightly different from the others. Even though we aim for quantification wherever possible, it is unrealistic to expect exactly the same results between all potential graders. The key is to aim for relative consistency between graders, which should be possible since AHP is performing pair-wise comparisons between the grades.

The process of pair-wise comparison is automated using a software program that converts the grades (from 1 to 10 on each quality for each product) to an AHP comparison matrix. Once the AHP calculations are complete, we can see how the software products grade relative to one another. Further details on the algorithm to transform our objectives measures into an AHP sorted ranking can be found in Smith et al. (2015a), which presents an analysis similar to the current one, except rather than studying GIS software, the domain of interest is psychometrics software.

For grading GIS software, we award a grade of 5 for “indifference.” For example, if the developer has not explicitly written about or documented extra measures to increase the performance of an otherwise sound product. We cannot dock marks for poor performance, and we cannot award marks for outstanding performance. This same situation appears often in portability and reusability grading.

We award marks of 1 for understandability (of the code) when no source code is available, since we cannot analyze the product’s understandability, so relative to any open source product the product’s understandability is very poor.

To demonstrate that the grading process is objective, 5 software products were graded by two reviewers. The final results were very similar, and the final grades nearly exactly the same. The main source of difference between gradings is the interpretation of the definition of correctness, and specifically what a requirements specification document entails. As long as each grader is consistent, the relative comparisons in the AHP results will be consistent between graders. Changes in perceived visibility of the software product also plays a major part in differences between grades. Information that is hard to find, or on a different site, can hurt a product’s grades, since not all reviewers will have the same luck in finding the information.

4. Summary of Results

The most up-to-date and complete grading of the 30 domain software products is available in an external repository at https://data.mendeley.com/datasets/6kprpvvr7/1 with a less verbose summary available in the Appendix.

Before grading the software qualities, we gathered general information about the products. Of the 30 GIS products, eight were associated with educational institutions. These institutions are the workplaces of the developers, or provide support for the projects financially. There are 19 open source products. The 30 software products are easily split into three main sets. These sets will be used to simplify the presentation of the software products throughout the remainder of this paper. First, there are six Desktop Geographical Information System (GIS) products, as shown in Table 2. These products have enormous feature sets and exist to obtain,
| Name                | Status | Open source | Language |
|---------------------|--------|-------------|----------|
| DIVA-GIS (Hijmans, 2011) | Dead   | No          | Java     |
| GRASS (GRASS Development Team, 2014) | Alive  | Yes         | C        |
| gvSIG (gvSIG Association, 2013) | Alive  | Yes         | Java     |
| QGIS (QGIS, 2014) | Alive  | Yes         | C++, Python |
| SAGA-GIS (Conrad and Wichmann, 2014) | Alive  | Yes         | C++      |
| uDig (Antonello et al., 2013) | Alive  | Yes         | Java     |

Table 2: Desktop GIS set

change, analyze and present a wide variety of geographical data. The next set consists of 12 stand-alone tools (Table 3) that perform specific tasks. These tools are much less feature-rich than the desktop GIS systems. Finally, there are 12 libraries and packages (Table 4) that enable programmers to develop their own software products using the functionality of the libraries/packages. Of these libraries, seven are written in Python, three in R, one in C, and one in C++.

Summary general information about the graded GIS software follows:

- 17 products have 5 or fewer developers. Eight projects have two or fewer developers.
- 5 products (GRASS, gvSIG, QGIS, OSSIM, PostGIS) have funding by The Open Source Geospatial Foundation (Foundation, 2014), whose goal is to support the development of open source geospatial software products.
- There are 9 dead products based on our 18 month time-frame for liveness.
- Of the 19 open source products, the GNU GPL license is the most popular (11/19). MIT (4/19) and BSD (3/19) licenses are also widely used. Closed source software, or “freeware” either provide no license, and explicit written terms of use, or an end user license agreement.
- Windows is well supported (29/30).
- C++ is the most popular language, in use by 13/30 products.

With respect to installability, 21/30 projects contained installation instructions, with 14 of the 21 having linear instructions. Therefore, more than half of the products analyzed did not contain linear installation instructions. Though, in 27/30 cases, installation was automated with the use of makefiles or scripts. So, the absence of linear installation instructions is partially justified in that the steps are taken automatically. Only two software products (NumPy and PostGIS) provided explicit post-installation tests to check the correctness of the installation. Eight products required software to be installed beforehand. Uninstallation automation is not provided in 13 of the 30 projects. However, deleting the software’s root directory or deleting the executables was normally sufficient to uninstall the software.
| Name                  | Status | Open Source | Language       |
|-----------------------|--------|-------------|----------------|
| Biomapper (Hirzel, 2009) | Dead   | No          | Borland Delphi |
| Conefor (Saura and Rubio, 2014) | Dead   | Yes         | C++            |
| CROP_VGT (Griguolo, 2005)      | Dead   | No          | Unclear        |
| CyberTracker (CyberTracker Conservation, Unclear) | Alive  | No          | C++, Java      |
| DesktopGarp (Scachetti-Pereira, Unclear) | Unclear | No          | C++            |
| FRAGSTATS (McGarigal, 2014)    | Dead   | No          | C++            |
| Lifemapper (Beach et al., 2014) | Unclear | Yes         | Python         |
| MARXAN (Possingham, 2012)      | Dead   | No          | C++            |
| Maxent (Schapire, 2011)        | Alive  | No          | Java           |
| openModeller (openModeller Developers, 2014) | Dead   | No          | C++            |
| OSSIM (OSGEO, 2014b)          | Alive  | Yes         | C++            |
| Zonation (C-BIG, 2014)         | Dead   | No          | C++            |

Table 3: Stand-alone tools set

| Name                  | Status | Open Source | Language       |
|-----------------------|--------|-------------|----------------|
| GDAL/OSGEO (OSGEO, 2014a) | Alive  | Yes         | C++            |
| GDL (Schellens, 2013)   | Alive  | Yes         | C++            |
| geopy (Tigas, 2014)     | Alive  | Yes         | Python         |
| landsat (Goslee, 2012)  | Dead   | Yes         | R              |
| NetworkX (NetworkX Dev. Team, 2014) | Alive  | Yes         | Python         |
| NumPy (NumPy Developers, 2014) | Alive  | Yes         | C, Python      |
| PostGIS (Ramsey et al., 2014) | Alive  | Yes         | C              |
| pyproj (Whitaker, 2013)  | Alive  | Yes         | Cython         |
| pyshp (GeospatialPython.com, 2013) | Alive  | Yes         | Python         |
| raster (Hijmans et al., 2014) | Alive  | Yes         | C              |
| rgdal (Bivand et al., 2014) | Alive  | Yes         | C, C++, R      |
| shapely (Toblerity, 2014) | Alive  | Yes         | Python         |

Table 4: Programming libraries set
As Figure 1 shows, programming libraries generally do well on installability. This is because these products can often be installed using just one step (9/12) using a package manager, like pip for Python software and CRAN for R software. GRASS and gvSIG, from the Desktop GIS set, also score high on installability, since these products include easy to use installers and have easy-to-follow, linear installation instructions. Poor cases of installability occur when the user must “jump hurdles” to obtain or install the software. Problems occur when users must do additional research, or follow an installation practice that requires an extra layer of software or “work-arounds”. For example the only supported way to install DIVA-GIS (native on Windows) on OS X is through Winebottler, an .exe packager for OS X. This is not a “normal” way to support OS X and relies on a third party for installation and portability. This is different from using a virtual machine for installing and using the software, as we have done for our measurement purposes. In the case of MARXAN and Confor’s command line tools, personal information (name, email) or email correspondence with the developers is required to obtain the software. Developers have every right to ask for this information before making the software available to the user, but this still adds complexity to the installation process.

As Figure 2 shows, correctness and verifiability score high for programming libraries and some desktop GIS systems, but not particularly well for the stand-alone tools. 18 systems used external libraries, with the stand-alone tools using external libraries less frequently than the desktop GIS or programming library sets. Some of the most relied-upon software include sp (written in R), GDAL and PostGIS for abstracting the handling and storage of spatial data. Requirements specification documents were very rare. Only three products (GRASS, GDL and pyshp) explicitly stated adherence to a specification. In GRASS, this specification is presented in a wiki that outlines the purpose, scope, overall description and specific requirements, such as performance and design constraints. While specification documents often do not exist, some projects contain other evidence of explicitly considering correctness. Doxygen or similar tools are used in projects such as SAGA-GIS, PostGIS and OSSIM to automatically generate documentation from the source code. This adds to correctness because the specified behaviour of the product is derived from the source code, and by maintaining them together the documentation and the code should be in sync. Another form of confidence building is automated testing. Five desktop GIS systems, and 10 programming libraries used automated testing. Though stand-alone tools show a general lack in automated testing (2/12). Without testing, requirements specification or other evidence, the conclusion is that stand-alone tools have not adequately considered the quality of correctness.
Reliability, overall, is very strong on the surface for all three sets of software products. As explained above, installation of the 30 products went smoothly for the most part. Terminal errors or other prohibitive problems during installation were rare and only occurred in two products: Lifemapper and OSSIM (both stand-alone tools). Initial testing of the products was less automated, and contained more room for error, especially if there are multiple steps in the getting started tutorial. There were no errors or other “breakages” for desktop GIS products or stand-alone tools during initial testing. However, a programming library, geopy, had a segfault error while running the getting started tutorial.

Surface robustness is considered in all 30 of the software products graded. By making simple typos and using purposely broken/poor input, we were successful in triggering errors in the software products, without the product crashing. All of the software contained some form of error handling, with variations on the style of display and amount of information given in the error message. These variations impact the usability of the product. Good information and prominent placement of blocking errors helps the user understand the errors. While the software all contains error handling, some software products, like raster, give difficult to understand and vague error messages, which provided little information on what the error was or how to proceed. On average, programming libraries performed better than desktop GIS systems and stand-alone tools, giving more informative and noticeable errors on the command line, as compared to the various methods of displaying errors in a GUI environment.

Surface performance is not explicitly discussed in 22/30 software products. GRASS and QGIS have sections of documentation related to performance. This documentation covers performance optimization measures taken by the developers, and/or benchmarks using test data. Performance is considered in one stand-alone tool (openModeller) in a document detailing the methods to profile the product’s performance. In the case of programming libraries, the task of achieving maximum performance lies with the end user. Just one programming library (PostGIS) had any documentation about performance considerations. Sometimes, like in the case of FRAGSTATS and GDAL/OGR, the only time performance is mentioned is when there are possible known memory leaks or other performance-related bugs.

Surface usability is strong for both desktop GIS products and programming libraries, as shown in Figure 3. Desktop GIS products contained a getting started tutorial most frequently, with 4/6 products, compared to 5/12 for stand-alone tools and 7/12 for programming libraries. These getting started tutorials normally contain a standard example directed toward first-time users. 29/30 of the software products contained a complete user manual. These user manuals vary in scope and length, but serve to inform the user of the software’s complete purpose,
design and functionality. The best user manuals come with the desktop GIS products. Their user manuals are logically organized into sections that cover all of the user’s interactions with the product, from pre-installation information (feature overview, marketing) to software design, to information and guides on using every facet of the software. The one product that does not contain a user manual is CROP_VGT. In this case, the getting started tutorial serves as the complete guide on how to use the software. Some of the user guides are more academic, such as the documentation for MARXAN, which consists of references to books, and external manuals written by others.

The layout and design of the software products is encompassed by usability. Design is more apparent in GUI applications, but design considerations are also apparent in command line software or programming libraries. For the most part, the expected “look and feel” of the software products are adhered to. Rarely, (e.g., Biomapper, OSSIM) some unusual choices are made for such things as the font or the GUI skin. There are a few rare cases where the design of the software makes important features more difficult to find than they could be. For instance, there is a lack of organization on the settings screen in Maxent. This is known as a problem with visibility, as described in Don Norman’s design principles (Norman, 2002).

In most cases, (27/30) the expected user characteristics are not documented. Conefor advises that you should be an advanced user to use the command line tools, but otherwise, developers rarely document any background knowledge that potential users should have before using the product.

Another aspect of usability to consider is the existence of a user support system. Other than direct email, and the issue tracker (if it exists, and if it is used for posting support requests) there are alternate methods of support, such as mailing lists, IRC (Internet Relay Chat), message boards, and FAQs (Frequently Asked Questions). Most frequently, 4/6 desktop GIS products had alternatives, like an IRC channel for uDig and a dedicated QGIS StackExchange tag for questions. Stand-alone tools (7/12) and programming libraries (6/12) also had alternatives for support. Deviating from the norm, some projects written in R, like raster, had no explicit support model.

Maintainability roughly varies with the size of the project. With the information available, size is difficult to quantify; however, the grader can form a feel for the size of the project from the number of developers and downloads, and the activity in the news sections and support channels. Based on the reviewer’s feel for project size, larger projects generally perform better on maintainability. The developers of small or closed-source projects do not always consider
maintainability, as shown in Figure 4. 29 products had multiple versions of the software, but often these past versions were not available for download. The user may not ever want to download these legacy versions, but having them available does not hurt, and improves visibility. 14 of the software products did not use an issue tracking tool, or asked for email correspondence to report bugs. Email correspondence is private, so the reported bugs are not known to all, which is bad for both visibility and maintainability. Of these 14 products, 10 are stand-alone tools. Out of the remaining 16 products that are using issue tracking, 14 of them were mostly dealing with corrective maintenance. Desktop GIS systems (5/6) and programming libraries (9/12) mostly used issue tracking tools. Stand-alone tools only used issue tracking in 2/12 cases (OSSIM and openModeller). When issue trackers were employed, the majority of the tickets have been closed for most products. Trac, GitHub, JIRA, and Sourceforge are the most popular issue tracking systems.

Version control systems are publicly used in desktop GIS (5/6) and programming libraries (9/12), but again, in just 2/12 cases for stand alone tools (OSSIM and openModeller). The developers of any of the graded products may be privately using version control systems, but there is no documentation suggesting so. Git (10) and SVN (7) are nearly equal in use among the graded software products.

The best cases of maintainability come from software products with developer’s guides. Four desktop GIS systems and two programming libraries contained developer’s guides. Any information associated with the process of adding new code to the project from internal or external contributors can be included in a developer’s guide. The software products that contain developer’s guides are: GRASS, gvSig, NetworkX, PostGIS, SAGA-GIS, uDig.

As an alternative to explicitly documenting the development process, the process can be implicit in the workflow of the tools employed. For example, products that use GitHub adhere to the processes of the Git version control system and the pull request system facilitated by GitHub.

Reusability scored high for desktop GIS and programming library products, but for different reasons. Five out of six desktop GIS systems contain ways to make reusability easy using APIs, and add-ons. An outstanding example, GRASS GIS, contains an API and an add-ons system. These systems provide the software product’s functionality to developers so that they can create their own functionality both inside GRASS and in their own programming projects. Programming libraries, on the other hand, provide reusability because the software product itself is the code and available for programmers to use for their own purposes.
For both desktop GIS and programming library software, documentation is important. Well-written and designed add-on API documentation can make it easier for developers to learn how to interact with the products. For stand-alone tools, reusability does not seem to be a primary concern. For these products, the developers either do not have the resources or requirements to develop an API or plug-in system.

Portability has been achieved for most of the software products, with 29 products supporting Windows and of these, 22 supported Linux, OS X or both. There are 7 Windows-only products. There exist many different ways to achieve portability including cross-platform build systems such as cmake, OS-specific branches in code, or by the use of a language easily compiled or interpreted on different systems. For example, languages like R and Python can be run on any modern OS. Therefore, the programming libraries set is graded very well on portability. In some cases, portability was explicitly identified as not being important, which means a lack of portability cannot be held against these products, since they have matched their own stated requirements. SAGA-GIS stated that support for OS X is possible, but the developers had not tested it. DesktopGarp explicitly stated that there are no plans for OS X/Linux support.

Understandability of the code, overall, is strong on the surface for all sets of software products. We examined the 19 open source products’ source code and found consistency in formatting, and in the cases of products with developers manuals, sometimes even code style guidelines (uDIG, OSSIM, NumPy) or formatting tools (PostGIS). Useful commenting is almost always used. In one case (pyproj), the source contains little formatting, and the grades were lowered accordingly. For larger projects such as the desktop GIS products, and particularly ones with developer’s guide, there are often design documents. Nine open source projects had a design document as a reference.

Interoperability is similar to reusability in that projects that require these facilities often support them well. This occurs primarily in the desktop GIS and programming library sets. These sets use external libraries more frequently, and support re-use via add-ons or directly via an API. For example, geopy is an API itself, but geopy interacts with many external services such as Google and Mapquest to obtain geocoding data.

Transparency seems to be roughly proportional to the size of the project, as illustrated in Figure 5. The more information the project has to display, the more often the developers have designed efficient ways to access this information. Ideally, projects have one web site with all information contained on it. In practice, projects often consist of multiple web sites that provide different services for the project. For example, a main site serves as a hub to external code hosting, download sites, issue trackers, and/or documentation. In this case, it is the grader’s task to discover these web sites and gather information about the project.

Key to the transparency of a product is whether its development process is defined. Any protocols that the developers use to add new code, keep track of issues or release new versions are ideally recorded, so that new developers, or users, can be informed. Ten projects had defined development processes. The most thorough information regarding development process was found in the developer’s guides. These guides cover development processes, software design, code style and more. Only 8 projects contained any developer-specific documentation section with 7 of them having explicit developer’s manuals. Of these 7, 5 were desktop GIS products and the other 2 were programming libraries. Six of the 7 projects with developer’s manuals have 5 or more developers. The desktop GIS set has excellent transparency, since these projects have large groups of developers to coordinate. Stand alone tools normally use self-made sites, so the relative transparency can vary, but, in general, this set of GIS software graded poorly in transparency, especially tools like Biomapper or Zonation.
Open source programming libraries can rely on code hosting services such as GitHub or SourceForge to consolidate information and tasks such as issue tracking and a wiki. Software packages available via repositories, such as R software in The Comprehensive R Archive Network (CRAN), can be given a web page to display information about the project.

Reproducibility is only partially considered in the 30 graded software products. Only four products (uDig, NumPy, shapely, GDAL/OGR) provide development setup information. In particular, shapely recommends the usage of a virtual development environment. GDAL/OGR includes a Vagrantfile, which enables the user to have access to a functioning virtual machine, loaded with the project source and tools as configured by Vagrant [Hashimoto and Bender 2014].

Access to sample data is provided by 24/30 projects. This sample data can be used in the getting started tutorial, or simply to illustrate the format of the data and to provide sample data for the user to play with. Sample data along with a getting started tutorial (see usability) adds to reproducibility (and correctness) since the output can be checked against what is stated in the tutorial. However, sample data is often not comprehensive with respect to the product’s functionality, so one cannot fully grade correctness using sample data. To fully grade correctness, a product must use a comprehensive test suite, as discussed in the results summary for correctness.

Once the grading has been finished, the overall impression of the products performance on all software qualities is evaluated using AHP with equal weights between all qualities, as shown in Figure 5. Stand-alone tools’ AHP grades are lower relative to the other two sets. This ranking is due to the generally poor performance of stand-alone tools on installability, correctness, maintainability, reusability, portability, understandability, transparency and reproducibility. Part of the reason for the relatively poor performance may be that these products have fewer developers.

5. Recommendations

Our recommendations assume the ideal case where the developers have the desire, time and resources to aim for high quality. That is, in the terminology of Gewaltig and Cannon (2012), the software is intended to be user ready, as opposed to review ready, or research ready. Not all developers will require a high grade on the template in Appendix A. However, if the work will be used for decisions that impact health, safety or financial concerns, or if the project is to be maintained going forward, then high quality should be the goal. Moreover, if the results obtained with the software are to be reproducible, documentation has a critical role.
An example from GIS that stands out on all measures is GRASS. Developers on other projects should look to GRASS as an example to emulate. This advice applies to projects outside of the GIS domain. In a paper studying SC software in the domain of oceanography, using the same methods as used in this paper, one of the recommendations was for oceanography developers to follow the example set by GRASS (Smith et al., 2015b). The success of GRASS is, of course, based on the hard work of the dedicated individuals that have contributed to it. However, the success should also be attributed to the existence of a clear software development process and an infrastructure of development support tools.

The full grading template in the Appendix should be taken as a set of criteria for developers of SC software to consider to ensure best development practices and product quality. Considering all of the items on the list is recommended, but based on the above results for the GIS domain, the authors have three main recommendations for developers:

1. **Ensure the project has a requirements specification document.** Correctness is a quality on which many software products suffered in our study. By definition, correctness requires a specification. For developers to claim correctness, they must have complete, consistent, unambiguous, and verifiable specifications detailing the operation of the software product. In this instance, if the software was graded more leniently, perhaps some of the more extensive and complete user manuals could be seen as requirements specification documents. Sometimes, they even included mathematical background. However, the nature of user manuals is to teach the end user about how to use the software product, not to provide requirements. The move to incorporate requirements is facilitated by the progress on this topic in SE. A structured template for requirements specification for SC software is provided by Smith and Lai (2005). Formal specification can also be applied
with tools such as Frama-C (CEA-LIST, 2014) for C or JML (Leavens, 2013) for Java.

2. **Provide multiple support methods.** Support for the product should not simply consist of directly emailing the customers. Mailing lists are better since they can be public, have been in use for many years and are relatively simple. Static methods of support such as an FAQ page or .hlp file (obsolete, Windows help format) are also useful, but do not allow for ad hoc support requests by users. “Alternative” methods of support should make support requests easier, and allow any person with the knowledge to respond. Some ideas for additional support methods include an IRC channel, a Stack Exchange (http://stackexchange.com/) tag for new questions, or opening the issue tracker up for support requests. Normally, an issue tracker is only for bug reports, but allowing support requests to be added via the issue tracker gives users another way to contact developers and to get support for an issue with the product. This adds to the usability of the product because simple support makes the product simpler to use. Opening the issue tracker to users can assist the developers with maintainability (finding bugs), usability (design visibility issues), and other quality improvements. Not all of the above measures are necessary, especially if the software product has relatively few users or features. In the end, the developers for each software package needs to determine the appropriate level of support for their project.

3. **Design product websites for maximum transparency; for open source projects, provide a developer’s guide.** Transparency of a product is important for developers because users with different backgrounds and intentions will be looking for information. Transparency played a large part in how quickly we could grade each product. Developers can make essential information about the project visible by creating well-designed and usable websites. Simple HTML websites are easy to maintain, and their design is straightforward. Web platforms such as Wordpress (Automattic, 2014) make creating and administering a blog and page style product website straightforward. There also exists full web solutions (like GitHub or SourceForge) to display product information and host source code, and other assets such as user manuals and issue trackers. For example, we used GitHub to host our project results summaries during the creation of this paper (https://github.com/adamlazz/DomainX). When developers start to mix two or three of the above methods for their own project, transparency is greatly reduced. Developers are tasked with keeping multiple sites up to date while developing the product. If the multiple sites are not up to date, the user might be misguided, and the management of the product suffers.

Transparency is especially important to consider for new team members or users that choose to look at the source and edit or contribute new code. The product’s lead developers should create developer’s guides as reference materials for these new developers. Ideally, all aspects of product development are represented. Information on the current state of development, product roadmap, design, and contribution guidelines for adding new code should all be included. These contribution guidelines can include any explicit coding standards or version control processes (e.g. creating a new branch for the patch changes). These processes increase maintainability because the developers have created a plan to execute when maintaining the source.

Once these steps have been taken, we would further recommend the use of a virtual development environment to ease reproducibility. These are quite simple to create nowadays, and
ensures that developers’ and testers’ environments are fully controlled. This makes it simple for new developers of the product to set up their development environment. While this recommendation mainly concerns developers, it is also possible that this environment can be used by end users for a complete, isolated view of the product that requires no set up from the user.

6. Conclusions

To provide feedback to the GIS software community, we systematically graded 30 software products associated with the domain. Using a multicriteria decision making method, AHP, we performed a pairwise analysis between each software product. The results were summarized and interpreted for trends.

For the state of practice in GIS software we found the following positive trends among the graded software:

- Products rarely have installation problems or problems with initial testing.
- Projects handle garbage input without problems, such as crashing the program or errantly proceeding with bad input. All GIS software products surveyed had some error handling, which adds to their robustness.

Our survey found the following negative trends:

- Developers rarely explain the background knowledge or fully explain the intended behaviour of the product with a requirements specification document. Without a complete specification document, the product cannot adequately be judged on correctness.
- Ideal or expected user characteristics are rarely stated, which makes it difficult for the user to determine if the product is right for them.
- Instructions for validating or checking installation to ensure it works correctly are rarely included in the graded software. If the user is unfamiliar with the software product, this information would be helpful to them.
- For people that want to contribute to the source code, identification of a coding standard should be provided, and there should be comments in the code indicating “what” is being done, but not “how” it is being done. Proper code documentation should include pointers to more information on the algorithms used in the code to improve the understandability of the software.
- Evidence that performance or maintainability are considered is rare. Lack of this information hurts the user’s impression of the product for these qualities.
- Though not a part of the software itself, the supporting web sites are still a part of the product. Having multiple web sites serving separate functions hurts transparency of the project. For example, having separate sites for the main product page, a repository site and a wiki site means users must hunt for information online that would be better gathered from a single well-designed web site.
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Appendix A. Full Grading Template

The table below lists the full set of measures that are assessed for each software product. The measures are grouped under headings for each quality, and one for summary information. Following each measure, the type for a valid result is given in brackets. Many of the types are given as enumerated sets. For instance, the response on many of the questions is one of “yes,” “no,” or “unclear.” The type “number” means natural number, a positive integer. The types for date and url are not explicitly defined, but they are what one would expect from their names. In some cases the response for a given question is not necessarily limited to one answer, such as the question on what platforms are supported by the software product. Case like this are indicated by “set of” preceding the type of an individual answer. The type in these cases are then the power set of the individual response type. In some cases a superscript * is used to indicate that a response of this type should be accompanied by explanatory text. For instance, if problems were caused by uninstall, the reviewer should note what problems were caused. An (I) precedes the question description when its measurement requires a successful installation.

Table A.5: Grading Template

| Summary Information |
|----------------------|
| Software name? (string) |
| URL? (url) |
| Educational institution (string) |
| Software purpose (string) |
| Number of developers (number) |
| How is the project funded (string) |
| Number of downloads for current version (number) |
| Release date (date) |
| Last updated (date) |
| Status ({alive, dead, unclear}) |
| License ({GNU GPL, BSD, MIT, terms of use, trial, none, unclear}) |
| Platforms (set of {Windows, Linux, OS X, Android, Other OS}) |
| Category ({concept, public, private}) |
| Development model ({open source, freeware, commercial}) |
| Publications using the software (set of url) |
| Publications about the software (set of url) |
| Is source code available? ({yes, no}) |
| Programming language(s) (set of {FORTRAN, Matlab, C, C++, Java, R, Ruby, Python, Cython, BASIC, Pascal, IDL, unclear}) |

Installability (Measured via installation on a virtual machine.)

| Are there installation instructions? ({yes, no}) |
| Are the installation instructions linear? ({yes, no, n/a}) |
| Is there something in place to automate the installation? ({yes*, no}) |
| Is there a specified way to validate the installation, such as a test suite? ({yes*, no}) |
| How many steps were involved in the installation? (number) |
| How many software packages need to be installed before or during installation? (number) |
| (I) Run uninstall, if available. Were any obvious problems caused? ({unavail, yes*, no}) |
Overall impression? (1 .. 10)

**Correctness and Verifiability**

Are external libraries used? ([yes*, no, unclear])
Does the community have confidence in this library? ([yes, no, unclear])
Any reference to the requirements specifications of the program? ([yes*, no, unclear])
What tools or techniques are used to build confidence of correctness? (string)
(I) If there is a getting started tutorial, is the output as expected? ([yes, no*, n/a])
Overall impression? (1 .. 10)

**Surface Reliability**

Did the software “break” during installation? ([yes*, no])
(I) Did the software “break” during the initial tutorial testing? ([yes*, no, n/a])
Overall impression? (1 .. 10)

**Surface Robustness**

(I) Does the software handle garbage input reasonably? ([yes, no*])
(I) For any plain text input files, if all new lines are replaced with new lines and carriage returns, will the software handle this gracefully? ([yes, no*, n/a])
Overall impression? (1 .. 10)

**Surface Performance**

Is there evidence that performance was considered? ([yes*, no])
Overall impression? (1 .. 10)

**Surface Usability**

Is there a getting started tutorial? ([yes, no])
Is there a standard example that is explained? ([yes, no])
Is there a user manual? ([yes, no])
(I) Does the application have the usual “look and feel” for the platform it is on? ([yes, no*])
(I) Are there any features that show a lack of visibility? ([yes, no*])
Are expected user characteristics documented? ([yes, no])
What is the user support model? (string)
Overall impression? (1 .. 10)

**Maintainability**

Is there a history of multiple versions of the software? ([yes, no, unclear])
Is there any information on how code is reviewed, or how to contribute? ([yes*, no])
Is there a changelog? ([yes, no])
What is the maintenance type? (set of [corrective, adaptive, perfective, unclear])
What issue tracking tool is employed? (set of [Trac, JIRA, Redmine, e-mail, discussion board, sourceforge, google code, git, none, unclear])
Are the majority of identified bugs fixed? ([yes, no*, unclear])
Which version control system is in use? ([svn, cvs, git, github, unclear])
Is there evidence that maintainability was considered in the design? ([yes*, no])
Are there code clones? ([yes*, no, unclear])
Overall impression? (1 .. 10)
### Reusability

Are any portions of the software used by another package? ([yes*, no])

Is there evidence that reusability was considered in the design? (API documented, web service, command line tools, ...) ([yes*, no, unclear])

Overall impression? ([1 .. 10])

### Portability

What platforms is the software advertised to work on? (set of {Windows, Linux, OS X, Android, Other OS})

Are special steps taken in the source code to handle portability? ([yes*, no, n/a])

Is portability explicitly identified as NOT being important? ([yes, no])

Convincing evidence that portability has been achieved? ([yes*, no])

Overall impression? ([1 .. 10])

### Surface Understandability (Based on 10 random source files)

Consistent indentation and formatting style? ([yes, no, n/a])

Explicit identification of a coding standard? ([yes*, no, n/a])

Are the code identifiers consistent, distinctive, and meaningful? ([yes*, no*, n/a])

Are constants (other than 0 and 1) hard coded into the program? ([yes*, no, n/a])

Comments are clear, indicate what is being done, not how? ([yes, no*, n/a])

Is the name/URL of any algorithms used mentioned? ([yes, no*, n/a])

Parameters are in the same order for all functions? ([yes, no*, n/a])

Is code modularized? ([yes, no*, n/a])

Descriptive names of source code files? ([yes, no*, n/a])

Is a design document provided? ([yes*, no, n/a])

Overall impression? ([1 .. 10])

### Interoperability

Does the software interoperate with external systems? ([yes*, no])

Is there a workflow that uses other softwares? ([yes*, no])

If there are external interactions, is the API clearly defined? ([yes*, no, n/a])

Overall impression? ([1 .. 10])

### Visibility/Transparency

Is the development process defined? If yes, what process is used. ([yes*, no, n/a])

Ease of external examination relative to other products considered? ([1 .. 10])

Overall impression? ([1 .. 10])

### Reproducibility

Is there a record of the environment used for their development and testing? ([yes*, no])

Is test data available for verification? ([yes, no])

Are automated tools used to capture experimental context? ([yes*, no])

Overall impression? ([1 .. 10])

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**Appendix B. Summary of Grading Results**

The full gradings of the 30 GIS software products are below. The most recent gradings are available at: [https://data.mendeley.com/datasets/6kprpvv7r7/1](https://data.mendeley.com/datasets/6kprpvv7r7/1) The column head-
ings correspond with the above questions from the grading template.
| Name             | Ins | Lin | Auto | Val | Steps | Pkgs | Uninstall                      |
|------------------|-----|-----|------|-----|-------|------|-------------------------------|
| DIVA-GIS         | Yes | Yes | Yes  | No  | 1     | 0    | No uninstall available        |
| GRASS            | Yes | Yes | Yes  | Yes | 1     | 2    | No problems                   |
| gvSIG            | Yes | Yes | Yes  | No  | 1     | 0    | No problems                   |
| QGIS             | Yes | No  | Yes  | No  | 2     | 1    | No uninstall available        |
| SAGA-GIS         | Yes | Yes | Yes  | No  | 1     | 1    | No uninstall available        |
| uDig             | Yes | Yes | Yes  | No  | 1     | 0    | No problems                   |
| Biomapper        | No  | N/A | Yes  | No  | 2     | 0    | No uninstall available        |
| Conefor          | No  | N/A | N/A  | No  | 2     | 0    | No uninstall available        |
| CROP_VGT         | Yes | Yes | N/A  | No  | 2     | 0    | No problems                   |
| CyberTracker     | Yes | Yes | Yes  | No  | 1     | 0    | No uninstall available        |
| DesktopGarp      | Yes | Yes | Yes  | No  | 2     | 0    | No uninstall available        |
| FRAGSTATS        | Yes | Yes | Yes  | No  | 1     | 0    | No problems                   |
| Lifemapper       | No  | N/A | Yes  | No  | 2     | 0    | No uninstall available        |
| MARXAN           | No  | N/A | Yes  | No  | 2     | 0    | No uninstall available        |
| Maxent           | Yes | No  | Yes  | No  | 1     | 0    | No problems                   |
| openModeller     | Yes | Yes | Yes  | No  | 1     | 0    | No problems                   |
| OSSIM            | No  | Yes | Yes  | No  | 1     | 12   | No problems                   |
| Zonation         | No  | N/A | N/A  | No  | 1     | 0    | No problems                   |
| GDAL/OGR         | Yes | No  | Yes  | No  | 1     | 2    | No uninstall available        |
| GDL              | Yes | Yes | Yes  | No  | 4     | 0    | No uninstall available        |
| geopy            | Yes | Yes | Yes  | No  | 1     | 0    | No problems                   |
| landsat          | No  | N/A | Yes  | No  | 1     | 2    | No problems                   |
| NetworkX         | Yes | Yes | Yes  | No  | 1     | 0    | No problems                   |
| NumPy            | Yes | Yes | Yes  | Yes | 3     | 0    | No uninstall available        |
| PostGIS          | Yes | No  | Yes  | Yes | 1     | 1    | No problems                   |
| pyproj           | Yes | Yes | Yes  | No  | 2     | 0    | No uninstall available        |
| pyshp            | Yes | Yes | Yes  | No  | 1     | 0    | No problems                   |
| raster           | No  | N/A | Yes  | No  | 1     | 1    | No problems                   |
| rgdal            | No  | N/A | Yes  | No  | 1     | 1    | No problems                   |
| shapely          | Yes | No  | Yes  | No  | 1     | 1    | No problems                   |

Table B.6: Installability grading results
| Name            | Std Lib | Req Spec Doc | Evidence               | Std Ex |
|-----------------|---------|--------------|------------------------|--------|
| DIVA-GIS        | No      | No           | None                   | Yes    |
| GRASS           | Yes     | Yes          | Programmers guide      | Yes    |
| gvSIG           | No      | No           | No                     | Yes    |
| QGIS            | Yes     | No           | Developers section     | N/A    |
| SAGA-GIS        | Yes     | No           | Doxygen                | N/A    |
| uDig            | Yes     | No           | Developers guide       | Yes    |
| Biomapper       | No      | No           | None                   | N/A    |
| Conefor         | No      | No           | No                     | N/A    |
| CROP_VGT        | No      | No           | None                   | N/A    |
| CyberTracker    | Yes     | No           | No                     | Yes    |
| DesktopGarp     | Yes     | No           | No                     | Yes    |
| FRAGSTATS       | Yes     | No           | None                   | Yes    |
| Lifemapper      | Yes     | No           | pydoc                  | Yes    |
| MARXAN          | No      | No           | None                   | N/A    |
| Maxent          | No      | No           | None                   | Yes    |
| openModeller    | Yes     | No           | None                   | Yes    |
| OSSIM           | No      | No           | Doxygen                | Yes    |
| Zonation        | No      | No           | None                   | Yes    |
| GDAL/OGR        | Yes     | No           | Doxygen                | N/A    |
| GDL             | Yes     | Yes          | Doxygen                | N/A    |
| geopy           | No      | No           | None                   | No     |
| landsat         | Yes     | No           | Extensive documentation| No     |
| NetworkX        | Yes     | No           | None                   | Yes    |
| NumPy           | Yes     | No           | None                   | Yes    |
| PostGIS         | Yes     | No           | Doxygen                | Yes    |
| proj             | No      | No           | Wrapper to PROJ.4 library | N/A |
| pyshp           | No      | Yes          | No                     | Yes    |
| raster          | Yes     | No           | None                   | Yes    |
| rgdal           | Yes     | No           | None                   | N/A    |
| shapely         | Yes     | No           | None                   | Yes    |

Table B.7: Correctness grading results
| Name            | Break during install | Break during initial test |
|-----------------|----------------------|---------------------------|
| DIVA-GIS        | No                   | No                        |
| GRASS           | No                   | No                        |
| gvSIG           | No                   | No                        |
| QGIS            | No                   | No                        |
| SAGA-GIS        | No                   | No                        |
| uDig            | No                   | No                        |
| Biomapper       | No                   | N/A                       |
| Conefor         | No                   | No                        |
| CROP_VGT        | No                   | No                        |
| CyberTracker    | No                   | No                        |
| DesktopGarp     | No                   | No                        |
| FRAGSTATS       | No                   | No                        |
| Lifemapper      | Yes, install command not given | No |
| MARXAN          | No                   | No                        |
| Maxent          | No                   | No                        |
| openModeller    | No                   | No                        |
| OSSIM           | Yes, installed wrong package | No |
| Zonation        | No                   | No                        |
| GDAL/OGR        | No                   | N/A                       |
| GDL             | No                   | N/A                       |
| geopy           | No                   | Yes, segfault             |
| landsat         | No                   | No                        |
| NetworkX        | No                   | No                        |
| NumPy           | No                   | No                        |
| PostGIS         | No                   | No                        |
| pyproj          | No                   | No                        |
| pyshp           | No                   | No                        |
| raster          | No                   | No                        |
| rgdal           | No                   | N/A                       |
| shapely         | No                   | No                        |

Table B.8: Reliability grading results
| Name             | Handle garbage input | Handle line ending |
|------------------|-----------------------|--------------------|
| DIVA-GIS         | Yes                   | N/A                |
| GRASS            | Yes                   | N/A                |
| gvSIG            | Yes                   | N/A                |
| QGIS             | Yes                   | N/A                |
| SAGA-GIS         | Yes                   | N/A                |
| uDig             | Yes                   | N/A                |
| Biomapper        | Yes                   | N/A                |
| Conefor          | Yes                   | N/A                |
| CROP_VGT         | Yes                   | N/A                |
| CyberTracker     | Yes                   | N/A                |
| DesktopGarp      | Yes                   | N/A                |
| FRAGSTATS        | Yes                   | N/A                |
| Lifemapper       | Yes                   | N/A                |
| MARXAN           | Yes                   | N/A                |
| Maxent           | Yes                   | N/A                |
| openModeller     | Yes                   | N/A                |
| OSSIM            | Yes                   | N/A                |
| Zonation         | Yes                   | N/A                |
| GDAL/OGR         | Yes                   | Yes (in scripts)   |
| GDL              | Yes                   | Yes (in scripts)   |
| geopy            | Yes                   | Yes (in scripts)   |
| landsat          | Yes                   | Yes (in scripts)   |
| NetworkX         | Yes                   | Yes (in scripts)   |
| NumPy            | Yes                   | Yes (in scripts)   |
| PostGIS          | Yes                   | N/A                |
| pyproj           | Yes                   | Yes (in scripts)   |
| pyshp            | Yes                   | Yes (in scripts)   |
| raster           | Yes                   | Yes (in scripts)   |
| rgdal            | Yes                   | Yes (in scripts)   |
| shapely          | Yes                   | Yes (in scripts)   |

Table B.9: Robustness grading results
| Name                | Evidence of performance considerations |
|---------------------|----------------------------------------|
| DIVA-GIS            | No                                     |
| GRASS               | Yes, performance-specific documentation|
| gvSIG               | No                                     |
| QGIS                | Yes, notes in wiki on performance      |
| SAGA-GIS            | No                                     |
| uDig                | No                                     |
| Biomapper           | No                                     |
| Conefor             | No                                     |
| CROP_VGT            | No                                     |
| CyberTracker        | No                                     |
| DesktopGarp         | No                                     |
| FRAGSTATS           | No                                     |
| Lifemapper          | No                                     |
| MARXAN              | No                                     |
| Maxent              | No                                     |
| openModeller        | Yes, notes in wiki on performance      |
| OSSIM               | No                                     |
| Zonation            | No                                     |
| GDAL/OGR            | No                                     |
| GDL                 | No                                     |
| geopy               | No                                     |
| landsat             | No                                     |
| NetworkX            | No                                     |
| NumPy               | No                                     |
| PostGIS             | Yes, performance tips in documentation|
| pyproj              | No                                     |
| pyshp               | No                                     |
| raster              | No                                     |
| rgdal               | No                                     |
| shapely             | No                                     |

Table B.10: Performance grading results
| Name          | GS tutorial | Std Ex | User Man | Look and feel | Visib Prob? | User char | Support                                           |
|---------------|-------------|--------|----------|----------------|-------------|-----------|--------------------------------------------------|
| DIVA-GIS      | Yes         | Yes    | Yes      | Yes            | No          | No        | Mailing list, email                              |
| GRASS         | Yes         | Yes    | Yes      | Yes            | No          | No        | Mailing Lists, forum                            |
| gvSIG         | Yes         | Yes    | Yes      | Yes            | No          | No        | Bug tracker, mailing list                        |
| QGIS          | No          | No     | Yes      | Yes            | No          | No        | Mailing Lists, Forum, StackExchange, chat       |
| SAGA-GIS      | No          | No     | Yes      | Yes            | No          | No        | Mailing list, forum                            |
| uDig          | Yes         | Yes    | Yes      | Yes            | No          | No        | Mailing list, Issue tracker, IRC                |
| Biomapper     | No          | No     | No       | Yes            | No          | No        | Discussion list, wiki                           |
| Conefor       | No          | No     | Yes      | Yes            | No          | Yes       | Email list                                       |
| CROP_VGT      | No          | No     | Yes      | No             | No          | No        | .hlp file, email                                |
| CyberTracker  | Yes         | Yes    | Yes      | Yes            | No          | No        | Facebook/Yahoo group, email                     |
| DesktopGarp   | Yes         | Yes    | Yes      | Yes            | No          | No        | Discussion list                                 |
| FRAGSTATS     | Yes         | Yes    | Yes      | Yes            | No          | No        | FAQ, email                                      |
| Lifemapper    | No          | No     | Yes      | Yes            | No          | No        | None                                             |
| MARXAN        | No          | No     | Yes      | Yes            | No          | No        | Mailing List, email                             |
| Maxent        | Yes         | No     | Yes      | Yes            | Yes         | Yes       | Discussion group                                |
| openModeller  | No          | No     | Yes      | Yes            | No          | No        | IRC, email                                      |
| OSSIM         | Yes         | Yes    | Yes      | No             | Yes*        | No        | IRC, Mailing list, Issue tracker                |
| Zonation      | No          | Yes    | Yes      | Yes            | No          | No        | Issue tracker, forums, wiki                     |
| GDAL/OGR      | No          | No     | Yes      | Yes            | No          | No        | Mailing list                                    |
| GDL           | No          | No     | Yes      | Yes            | No          | No        | Docs, readme, forums                            |
| geopy         | Yes         | Yes    | Yes      | Yes            | No          | No        | Github Issues                                   |
| landsat       | No          | No     | Yes      | Yes            | No          | No        | Email                                            |
| NetworkX      | Yes         | Yes    | Yes      | Yes            | No          | No        | Issue tracker, mailing list                     |
| NumPy         | Yes         | Yes    | Yes      | Yes            | No          | No        | GitHub, Mailing List                            |
| PostGIS       | Yes         | Yes    | Yes      | Yes            | No          | No        | IRC, Mailing list, ticket tracker, commercial support, Stack Exchange |
| pyproj        | No          | No     | Yes      | Yes            | No          | No        | Issue tracker                                    |
| pyshp         | Yes         | Yes    | Yes      | Yes            | No          | No        | Issue tracker, email, commercial support         |
| raster        | Yes         | Yes    | Yes      | Yes            | Yes         | No        | None. But you can find the developers email     |
| rgdal         | No          | No     | Yes      | Yes            | No          | No        | None explicit, email?                           |
| shapely       | No          | Yes    | Yes      | No             | No          | No        | Github                                           |

Table B.11: Usability grading results, * has a visibility problem with the settings screen layout
| Name              | Mul Ver | Code rw | Chlog | Type | Issue track tool | Bugs fixes | CVS | Evid |
|-------------------|---------|---------|-------|------|------------------|-------------|-----|------|
| DIVA-GIS         | Yes     | N/A     | Yes   | N/A  | Email            | N/A         | N/A | No   |
| GRASS            | Yes     | PM      | Yes   | C    | Trac             | Yes         | SVN | PM   |
| gvSIG            | Yes     | DG      | No    | N/A* | N/A*             | SVN         | No  |      |
| QGIS             | Yes     | Yes     | Yes   | C    | Redmine          | Git         | No  |      |
| SAGA-GIS         | Yes     | Yes     | Yes   | C    | Trac             | No          | SVN | Yes  |
| uDig             | Yes     | Yes     | Yes   | C    | JIRA             | Git         | Yes |      |
| Biomapper        | Yes     | N/A     | Yes   | N/A  | Email            | N/A         | N/A | No   |
| Conefor          | Yes     | No      | No    | N/A  | N/A              | N/A         | N/A | N/A  |
| CROP_VGT         | Yes     | N/A     | Yes   | N/A  | N/A              | N/A         | N/A | N/A  |
| CyberTracker     | Yes     | N/A     | Yes   | N/A  | N/A              | N/A         | N/A | No   |
| DesktopGarp      | Yes     | N/A     | No    | N/A  | N/A              | N/A         | N/A | N/A  |
| FRAGSTATS        | Yes     | N/A     | Yes   | N/A  | Email            | N/A         | N/A | No   |
| Lifemapper       | Yes     | No      | No    | N/A  | N/A              | N/A         | N/A | Yes  |
| MARXAN           | No      | N/A     | No    | N/A  | Email            | N/A         | N/A | No   |
| Maxent           | Yes     | N/A     | NC    | N/A  | N/A              | N/A         | Git | No   |
| openModeller     | Yes     | No      | Yes   | C    | Sourceforge      | Yes         | SVN | No   |
| OSSIM            | Yes     | No      | Yes   | C    | Trac             | Yes         | Git | Doxygen |
| Zonation         | Yes     | N/A     | Yes   | C    | Redmine          | Yes         | N/A | No   |
| GDAL/OGR         | Yes     | No      | Yes   | C    | Trac             | SVN         | No  |      |
| GDL              | Yes     | Yes     | Yes   | C    | Sourceforge      | CVS         | No  |      |
| geopy            | Yes     | No      | Yes   | A    | GitHub           | Yes         | Git | No   |
| landsat          | Yes     | No      | No    | N/A  | N/A              | N/A         | N/A | No   |
| NetworkX         | Yes     | DG      | Yes   | C, P | GitHub           | Yes         | Git | No   |
| NumPy            | Yes     | No      | Yes   | C    | GitHub           | Yes         | Git | No   |
| PostGIS          | Yes     | DG      | Yes   | C    | Trac             | SVN         | No  |      |
| pyproj           | Yes     | No      | No    | C    | Google Code      | No          | Git | No   |
| pyshp            | Yes     | No      | Yes   | C    | Google Code      | Yes         | Git | No   |
| raster           | Yes     | N/A     | Yes   | N/A  | N/A              | N/A         | N/A | No   |
| rgdal            | Yes     | No      | Yes   | N/A  | N/A              | SVN         | No  |      |
| shapely          | Yes     | No      | Yes   | C    | GitHub issues    | Yes         | Git | No   |

Table B.12: Maintainability grading results

PM means Programmer’s manual, DG means Developer’s Guide, NC means not complete, C means Corrective, P means Perfective, A means Adaptive, * Need account to view issue tracker, no software showed code clones.
| Name          | Portions reused | Evid                          |
|---------------|-----------------|-------------------------------|
| DIVA-GIS      | No              | No                            |
| GRASS         | Yes add-ons     | API documentation            |
| gvSIG         | Yes extensions  | No                            |
| QGIS          | Yes plugins     | Yes plugins                   |
| SAGA-GIS      | Yes API         | API documentation            |
| uDig          | Yes plugins     | Plugin documentation         |
| Biomapper     | No              | No                            |
| Conefor       | No              | No                            |
| CROP_VGT      | No              | No                            |
| CyberTracker  | No              | No                            |
| DesktopGarp   | No              | No                            |
| FRAGSTATS     | No              | No                            |
| Lifemapper    | Not shown       | Web service                  |
| MARXAN        | No              | No                            |
| Maxent        | Yes API         | No                            |
| openModeller  | Yes this is a framework | Yes                  |
| OSSIM         | Yes API         | No                            |
| Zonation      | No              | No                            |
| GDAL/OGR      | Yes API         | API documentation            |
| GDL           | Yes             | No                            |
| geopy         | No              | No                            |
| landsat       | No              | No                            |
| NetworkX      | Yes             | No                            |
| NumPy         | Yes             | No                            |
| PostGIS       | Yes             | No                            |
| pyproj        | Yes             | No                            |
| pyshp         | Yes             | No                            |
| raster        | Yes             | No                            |
| rgdal         | Yes             | API documentation            |
| shapely       | Yes             | API documentation            |

Table B.13: Reusability grading results, Evid means Evidence
| Name          | Platform     | Port in code                          | Not important? | Evid      |
|--------------|--------------|---------------------------------------|----------------|-----------|
| DIVA-GIS     | WIN OSX     | N/A                                   | No             | N/A       |
| GRASS        | WIN LIN OSX  | Tools to create installer/ packages   | N/A            | N/A       |
| gvSIG        | WIN LIN     | Makefile                              | No             | No        |
| QGIS         | WIN LIN OSX | Cross platform code                   | N/A            | No        |
| SAGA-GIS     | WIN LIN     | Cross platform code                   | Yes, with OS X | No        |
| uDig         | WIN LIN OSX | Eclipse                               | N/A            | N/A       |
| Biomapper    | WIN         | N/A                                   | No             | N/A       |
| Conefor      | WIN LIN OSX | Unclear                               | No             | No        |
| CROP_VGT     | WIN         | N/A                                   | N/A            | N/A       |
| CyberTracker | WIN ANDROID | N/A                                   | No             | N/A       |
| DesktopGarp  | WIN         | N/A                                   | Yes. No plans for Mac/Unix | N/A |
| FRAGSTATS    | WIN         | N/A                                   | No             | N/A       |
| Lifemapper   | WIN LIN OSX | Python                                | N/A            | N/A       |
| MARXAN       | WIN LIN OSX | N/A                                   | No             | N/A       |
| Maxent       | JAVA        | Java or .bat                          | N/A            | N/A       |
| openModeller | WIN LIN OSX | Platform specific installation        | N/A            | N/A       |
| OSSIM        | WIN LIN OSX | Compilation steps, platform specific code | No            | N/A       |
| Zonation     | WIN         | N/A                                   | N/A            | N/A       |
| GDAL/OGR     | WIN LIN OSX | Differences in makefile               | N/A            | N/A       |
| GDL          | LIN OSX     | N/A                                   | N/A            | N/A       |
| geopy        | WIN LIN OSX | Python                                | N/A            | N/A       |
| landsat      | WIN LIN OSX | R                                     | N/A            | N/A       |
| NetworkX     | WIN LIN OSX | Python                                | N/A            | N/A       |
| NumPy        | WIN LIN OSX | Python                                | N/A            | N/A       |
| PostGIS      | WIN LIN OSX | Differences in makefile               | No             | N/A       |
| pyproj       | WIN LIN OSX | Python                                | N/A            | N/A       |
| pyshp        | WIN LIN OSX | Python                                | N/A            | N/A       |
| raster       | WIN LIN OSX | R                                     | N/A            | N/A       |
| rgdal        | WIN LIN OSX | R                                     | N/A            | N/A       |
| shapely      | WIN LIN OSX | Python                                | N/A            | N/A       |

Table B.14: Portability, Evid means Evidence
| Name            | Indent Code std | Cons Id | Cnstnts Cmnts | URL | Params Mdlr | File names | Design doc |
|-----------------|----------------|---------|---------------|-----|-------------|------------|------------|
| DIVA-GIS        | N/A            | N/A     | N/A           | N/A | N/A         | N/A        | N/A        |
| GRASS           | Yes            | No      | Yes           | Yes | Yes         | Yes        | Yes        |
| gvSIG           | Yes            | No      | Yes           | No  | Yes         | Yes        | Yes        |
| QGIS            | Yes            | No      | Yes           | Yes | Yes         | Yes        | Yes No     |
| SAGA-GIS        | Yes            | No      | Yes           | Yes | No          | Yes        | Yes        |
| uDig            | Yes            | Yes     | Yes           | Yes | Yes         | Yes        | Yes No     |
| Biomapper       | N/A            | N/A     | N/A           | N/A | N/A         | N/A        | N/A        |
| Conefor         | Yes            | No      | Yes           | No  | Yes         | Yes No     |
| CROP_VGT        | N/A            | N/A     | N/A           | N/A | N/A         | N/A        | N/A        |
| CyberTracker    | N/A            | N/A     | N/A           | N/A | N/A         | N/A        | N/A        |
| DesktopGarp     | N/A            | N/A     | N/A           | N/A | N/A         | N/A        | N/A        |
| FRAGSTATS       | N/A            | N/A     | N/A           | N/A | N/A         | N/A        | N/A        |
| Lifemapper      | No             | No      | Yes           | No  | Yes         | Yes No     |
| MARXAN          | N/A            | N/A     | N/A           | N/A | N/A         | N/A        | N/A        |
| Maxent          | N/A            | N/A     | N/A           | N/A | N/A         | N/A        | N/A        |
| openModeller    | Yes            | No      | Yes           | Yes | Yes         | Yes No     |
| OSSIM           | Yes            | Yes     | Yes           | Yes | Yes         | Yes No     |
| Zonation        | N/A            | N/A     | N/A           | N/A | N/A         | N/A        | N/A        |
| GDAL/OGR        | Yes            | No      | Yes           | No  | Yes         | Yes No     |
| GDL             | Yes            | No      | Yes           | Yes | Yes         | Yes        | Yes        |
| geopy           | Yes            | No      | Yes           | Yes | Yes         | Yes No     |
| landsat         | No             | No      | Yes           | No  | Yes         | Yes No     |
| NetworkX        | Yes            | No      | Yes           | No  | Yes         | Yes Yes    |
| NumPy           | Yes            | Yes     | Yes           | No  | Yes         | Yes Yes    |
| PostGIS         | Yes            | No      | Yes           | No  | Yes         | Yes Yes    |
| pyproj          | No             | No      | Yes           | No  | Yes         | Yes No     |
| psyshp          | Yes            | No      | Yes           | Yes | Yes         | Yes No     |
| raster          | Yes            | No      | Yes           | Yes | Yes         | Yes No     |
| rgdal           | Yes            | No      | Yes           | No  | Yes         | Yes No     |
| shapely         | Yes            | No      | Yes           | No  | Yes         | Yes No     |

Table B.15: Understandability grading results
| Name              | Ext systems                                      | Workflow     | API |
|-------------------|-------------------------------------------------|--------------|-----|
| DIVA-GIS          | ArcView                                         | No           | N/A |
| GRASS             | Many                                            | Not explicit | Yes |
| gvSIG             | Other softwares in project                     | Not explicit | Yes |
| QGIS              | GDAL framework on OS X                          | Not explicit | Yes |
| SAGA-GIS          | wxWidgets                                       | Not explicit | API |
| uDig              | Eclipse Rich Client Platform                    | Not explicit | Yes |
| Biomapper         | None                                            | No           | None|
| Conefor           | None                                            | Yes          | N/A |
| CROP_VGT          | None                                            | Not explicit | No  |
| CyberTracker      | Android/Windows phones                          | Not explicit | N/A |
| DesktopGarp       | Microsoft XML Parser                            | Not explicit | No  |
| FRAGSTATS         | ERSI ArcGIS ArcInfo used in tutorial            | ArcGIS       | N/A |
| Lifemapper        | PostgreSQL PostGIS GISs Web etc                 | Not explicit | Yes |
| MARXAN            | None                                            | No           | N/A |
| Maxent            | None                                            | No           | Yes |
| openModeller      | GBIF specisLink WCS                             | Yes          | Yes |
| OSSIM             | Plugins                                         | Not explicit | Yes |
| Zonation          | None                                            | Not explicit | N/A |
| GDAL/OGR          | libgdal Numpy                                   | Not explicit | Yes |
| GDL               | In software requirements                        | Not explicit | N/A |
| geopy             | Many third party services                       | Not explicit | Yes |
| landsat           | sp rgdal                                        | Not explicit | Yes |
| NetworkX          | NumPy SciPy GraphViz and more                   | Not explicit | Yes |
| NumPy             | SciPy stack                                     | Not explicit | Yes |
| PostGIS           | PostgreSQL                                      | Not explicit | Yes |
| pyproj            | Interface to Proj.4 library                     | No           | Yes |
| pyshp             | None                                            | Not explicit | Yes |
| raster            | sp                                              | Not explicit | Yes |
| rgdal             | sp                                              | Not explicit | Yes |
| shapely           | libgeos                                         | Not explicit | Yes |

Table B.16: Interoperability, ‘Conefor input generating GIS plugins
| Name             | Dev process           | External exam |
|------------------|-----------------------|---------------|
| DIVA-GIS         | No                    | 5             |
| GRASS            | Yes, developer’s guide| 10            |
| gvSIG            | Yes, developer’s guide| 4             |
| QGIS             | Yes, developer’s guide| 8             |
| SAGA-GIS         | Yes, developer’s guide| 7             |
| uDig             | Yes, developer’s guide| 10            |
| Biomapper        | No                    | 3             |
| Conefor          | No                    | 6             |
| CROP VGT         | No                    | 4             |
| CyberTracker     | No                    | 6             |
| DesktopGarp      | No                    | 7             |
| FRAGSTATS        | No                    | 6             |
| Lifemapper       | No                    | 6             |
| MARXAN           | No                    | 4             |
| Maxent           | No                    | 9             |
| openModeller     | No                    | 6             |
| OSSIM            | No                    | 6             |
| Zonation         | No                    | 4             |
| GDAL/OG               | No                    | 4             |
| GDAL             | Yes, HACKING file     | 8             |
| geopy            | No                    | 9             |
| landsat          | No                    | 5             |
| NetworkX         | Yes, developer’s guide| 9             |
| NumPy            | No                    | 4             |
| PostGIS          | Yes, developer’s guide| 8             |
| pyproj           | No                    | 6             |
| pyshp            | No                    | 9             |
| raster           | No                    | 9             |
| rgdal            | No                    | 4             |
| shapely          | No                    | 9             |

Table B.17: Visibility grading results
| Name            | Dev env | Ver test data                                           | Tools capture exp context |
|-----------------|---------|--------------------------------------------------------|---------------------------|
| DIVA-GIS        | No      | Sample data not for verification                       | None                      |
| GRASS           | No      | Sample data and test suite                             | None                      |
| gvSIG           | No      | Tests exist                                            | None                      |
| QGIS            | No      | Sample data available and test suite available         | No                        |
| SAGA-GIS        | No      | Tests available                                        | None                      |
| uDig            | Yes     | Sample data and test suite                             | None                      |
| Biomapper       | No      | No                                                      | None                      |
| Conefor         | No      | Sample data not for verification                       | None                      |
| CROP_VGT        | No      | No                                                      | None                      |
| CyberTracker    | No      | Sample data not for verification                       | None                      |
| DesktopGarp     | No      | No                                                      | None                      |
| FRAGSTATS       | No      | Yes                                                     | None                      |
| Lifemapper      | No      | Sample data not for verification                       | None                      |
| MARXAN          | No      | No                                                      | No                        |
| Maxent          | No      | Sample data not for verification                       | No                        |
| openModeller    | No      | Sample data and test suite                             | None                      |
| OSSIM           | No      | Yes and test suite                                     | None                      |
| Zonation        | No      | Sample data not for verification                       | None                      |
| GDAL/OGR        | No      | Tests                                                   | Vagrantfile               |
| GDL             | No      | Test suite                                              | None                      |
| geopy           | No      | Test suite                                              | No                        |
| landsat         | No      | No                                                      | None                      |
| NetworkX        | No      | Test suite                                              | No                        |
| NumPy           | Yes     | Test suite                                              | None                      |
| PostGIS         | No      | Yes test suite, make check                              | None                      |
| pyproj          | No      | Test suite                                              | None                      |
| pyshp           | No      | Test suite                                              | None                      |
| raster          | No      | No                                                      | None                      |
| rgdal           | No      | Tests available                                         | None                      |
| shapely         | No*     | Tests available                                         | None                      |

Table B.18: Reproducibility, *Virtual environment preferred