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Free and open source geographic information tools for landscape ecology

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ABSTRACT

Geographic Information tools (GI tools) have become an essential component of research in landscape ecology. In this article we review the use of GIS (Geographic Information Systems) and GI tools in landscape ecology, with an emphasis on free and open source software (FOSS) projects. Specifically, we introduce the background and terms related to the free and open source software movement, then compare eight FOSS desktop GIS with proprietary GIS to analyse their utility for landscape ecology research. We also provide a summary of related landscape analysis FOSS applications, and extensions. Our results indicate that (i) all eight GIS provide the basic GIS functionality needed in landscape ecology, (ii) they all facilitate customisation, and (iii) they all provide good support via forums and email lists. Drawbacks that have been identified are related to the fact that most projects are relatively young. This currently affects the size of their user and developer communities, and their ability to include advanced spatial analysis functions and up-to-date documentation. However, we expect these drawbacks to be addressed over time, as systems mature. In general, we see great potential for the use of free and open source desktop GIS in landscape ecology research and advocate concentrated efforts by the landscape ecology community towards a common, customisable and free research platform.

Contents

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1. Introduction

Modern landscape ecology research aims to study the variation in landscapes over multiple spatial and temporal scales (IALE, 1998). Geographic Information Systems (GIS) are increasingly being used as the principal 'tool' for such digital exploration of variation in landscapes, as they provide the necessary functions for spatial data collection, management, analysis and representation (Turner et al., 2001; Longley et al., 2005; Steiniger and Weibel 2009). While these tools provide new and critical ways of understanding our planet, we propose that GIS software used for Landscape Ecology (LSE) research should also fulfil several critical requirements other than simply providing basic GIS functionality. Specifically, we advocate that (i) to ensure world wide development, advancement and application of LSE principles and solutions, sophisticated and customisable GIS software also need be made available to developing nations that cannot afford expensive proprietary software. (ii) Research should not be limited by the functionality provided by a GIS platform. That is, options for customisation and functional enhancements are necessary to advance LSE science and solutions. (iii) GIS software should allow LSE experiments to be repeatable and results to be reproducible by other researchers — a fundamental requirement of science. This is only possible if all conditions of an experiment can be studied, i.e. data and algorithm implementation. (iv) Furthermore, developed models and algorithms should not need to be reimplemented by others in order to continue research or validate previous results. Thus, researchers should have access to libraries of the original models for analysis, validation, development and implementation.

Proprietary GIS software, such as ESRI's ArcGIS or Pitney Bowes' MapInfo, can fulfil the requirements of functionality, customisation and extensibility, and they may even have a low price tag (e.g. Manifold or IDRISI). However, they typically fall short with respect to research needs in terms of examinability of (algorithm) implementation and the distribution/application of newly developed models, since the original software is required to run the model. The reason for failing those requirements is to be found in software licenses that are applied by companies that offer proprietary software. Therefore, we advocate that GIS software that could fulfil the proposed requirements should be distributed with licenses that grant more freedoms of use and that support openness, such as licenses used by Free and Open Source Software (FOSS) GIS projects.

Over the last years the paradigm of Free and Open Source Software development has taken root in the GIS community, resulting in the creation of several very sophisticated GIS software projects whose aim is to develop free software for numerous purposes, ranging from Internet map server applications (e.g. the MapServer project), and spatial database management systems to store geographic data (e.g. PostGIS), to desktop GIS for data editing and analysis (e.g.; QGIS, SAGA, etc.) Here, the term 'free software' is not used in the sense of 'free-of-cost software'. Rather it addresses the freedoms of the user to freely use, study, modify, and distribute software (and will be discussed more fully in latter sections).

While the emphasis of this paper is on free and open source Geographic Information Tools for Landscape Ecology (LSE), we note that this article is not the first to discuss the utility of open source software for environmental research. For example, Jolma et al. (2008a) outline four case studies (workflows) taken from the domain of environmental modelling and management, and describe how free and open source software can be used to complete several workflow tasks, ranging from data collection, to simulation and map compilation. In two additional articles, Steiniger and Bocher (2009) argue for the use of open source GIS in GIScience, and Rey (2009) describes the utility and challenges of applying open source models within the spatial analysis research community. Introductory and advanced text on the use of free and open source GIS software are also provided by Sherman (2008) and Hall and Leahy (2008). In addition, Neteler and Mitasova's (2008) book focuses exclusively on the GIS software GRASS, and provides basic and advanced information on spatial analysis with this platform.

The overall goal of this paper is to provide the Landscape Ecology community with an in-depth, easy to understand and useful guide to the vast free GIS resources created by FOSS projects, with an emphasis on desktop GIS projects suitable for LSE analysis. To achieve this we will introduce the history and terminology of free and open source software development. Then we analyse the use of GIS in landscape ecology and introduce several categories of GIS software that can help to perform landscape monitoring and analysis tasks. Next, we will present eight Free and Open Source (FOS) desktop GIS and discuss their (LSE) functionality. This will be followed by a comparison between FOS GIS and proprietary software with an emphasis on functionality, software development, support, and user freedoms to provide insight into the weaknesses and strengths of both software license models. A list of acronyms and terms found in this review will then be provided.

2. What does "free software" and "open source" mean?

To better appreciate GIS needs of Landscape Ecology (LSE) and the available free and open source desktop GIS, it is important to understand the terms that are frequently used in the free and open source model. Therefore, we will first provide a brief historical context of the free and open source model and movement, then explain what is meant by 'free' and 'open source' and explain why we speak of 'free-of-cost' and 'proprietary' software rather than 'non-/commercial' software.

2.1. Why does free and open source software exists?

A review of digital computing reveals that the free exchange of software and free access to source code is not just a phenomenon of the last 20 years, but extends back some 50+ years. When the first (mainframe) computers were sold by companies, such as IBM and Bell, hardware and software were bundled together. From the 1950–70s, programmers from these companies collaborated with programmers from universities and research institutes to improve software and to write new software. An essential component to this collaboration was that the source code was *open* (i.e., it was uncompiled text that could be read, written and understood by programmers) since this was the most practical way to learn how software and hardware worked together (Grassmuck, 2004; Stallman, 1999; Johnson, 1999; Levy, 1984).

In the early 1960's with the development of ARPANET (the predecessor of the Internet), the possibility to send electronic messages greatly supported this free exchange of software and source code. However, in the late 1960s the anti-trust legal battles against IBM and the splitting of AT&T started to change this collaboration. Around 1969 IBM started to separate software from hardware (called: unbundling), and software was considered more and more as single product (Grassmuck, 2004). The splitting and privatisation of AT&T in 1984 was a driver for closing the source code of the Unix operating system. Two other factors supported recognising software as a separate product that needs to be protected. The first factor involved changes in the patent laws of the US in 1981. This provided protection for the implementation of mathematical formulas in software (see Diamond v. Diehr, 450 U.S. 175, 1983). The second factor was the emergence of the personal computer, and with it a new type of computer user whose work did not focus on software but on content, i.e. texts, pictures, calculations, music, etc, (Grassmuck, 2004).

Unsatisfied with the emerging situation where programmers and companies protected their software by closing their source code, Richard Stallman, from MIT labs, initiated the GNU-Project in 1983/1984. The aim of this project was to develop a complete package of software, including a Unix-like operating system, that is *free* and open to everybody, and that does not contain any proprietary components

(Stallman, 1999; www.gnu.org). Thus, the term 'free' was meant in terms of granting freedoms of use and modification. To protect these freedoms a new type of license, the General Public License (see below), was established and the Free Software Foundation was created to finance and guide the GNU project. When Stallman introduced the *freedoms of free use and modification* he not only focused on obtaining software with rich functionality and of high quality contributed to by a community, he also wanted to make people aware that sharing knowledge and helping others is a cornerstone of a social and ethical society (Stallman, 1999) — and, in our view, is a requirement for technological and scientific advancement.

The GNU project has laid out a basis and motivation for thousands of other projects that aim to develop Free and Open Source Software (FOSS). These projects not only develop software that can replace existing proprietary software (e.g. OpenOffice vs. Microsoft Office), but often also create software for specific purposes — since existing (proprietary) software solutions seldom provide the desired functionality for all users. Indeed, surveys show that not only individuals and research groups (with the same needs) found such software projects, but also companies and public administrations (Wheeler 2007; Steiniger and Bocher in press). Two arguments for public administration support of FOSS are (i) the opportunity for greater influence on the implementation of specific functionality that fits their needs, and (ii) the option of free (in-house) distribution of the software by saving licensing costs. Similarly, companies appreciate the option to share the development costs with other companies or even the FOSS community (Wheeler, 2007).

2.2. Free-of-cost vs. free and open source

We have already used the term 'free and open source software', and its abbreviation FOSS, several times in the first sections of this article. Now it is time to elaborate more fully on (i) what is meant when we speak of 'free' software, and (ii) why the term 'open source' should not be used alone. This distinction is important for members of the LSE community to recognise as they may choose to (i) use free software for their research; (ii) be involved in (GIS) software development and need to select a license for a new software project; or (iii) integrate their own developments with free software.

In the English language the term 'free' has at least two meanings. On the one hand 'free' is used as in 'free beer', i.e. referring to free-of-cost. On the other hand 'free' is related to freedom, as in 'free speech' (Stallman, 2007). Obviously there is a large difference in the semantics but this difference is often neglected by people when considering software. The Free Software Foundation (FSF, www.fsf.org) has introduced a definition of "free software". Essentially this definition does not define software as 'free' in terms of free-of-cost but in referring to four freedoms of use that a software license must address:

(1) the freedom to run the program, for any purpose (e.g., may it be educational or business),
(2) the freedom to study and adapt the program for ones own needs,
(3) the freedom to redistribute the program, and
(4) the freedom to improve the program and to release these improvements to the public (see http://www.gnu.org/philosophy/free-sw.html).

As the official definition further points out, access to the source code of a computer program is a precondition for freedoms (2) and (4). The definition does not make any statement whether the program has to be offered free of charge or not. With respect to this fact it is a mistake to classify software into 'free'- and 'commercial'-software, because "free (and open source) software" can also be sold. Rather, it is appropriate to classify software into 'free' and 'proprietary' software to indicate the relation to the freedoms (of use, modification and distribution) that are granted to the user. Using the term 'open source' alone to describe 'free' software is also inappropriate, as the term does not make a statement regarding whether the source code can be studied only — or modified and distributed as well.

There are several software licenses that conform to these principles (see http://www.gnu.org/licenses/licenses.html), but probably the best known software licenses are the GNU General Public License (GNU GPL) and the GNU Lesser/Library General Public License (GNU LGPL). An important property of the GNU GPL is that it contains a license term that allows the redistribution of the software *only* under the same license conditions (see license term 2.b of Version 2). Thus, the license protects the freedoms by "not allowing the application of a different license than those that is used for the original software". This means that (i) a new code contribution that adds functionality based on existing code, and (ii) a change of the original code, are still covered by the GPL license and can not be relicensed. The inclusion of such a term into the license itself has been called *copyleft*-ing (FSF, 2008a). The difference between the GPL and LGPL, a derived license, is that the LGPL does impose the license terms only on the program delivered with that license and not on other programs that link to it, or utilise provided functionality. For instance, if a library that contains spatial analysis functions is covered by the GPL, it can not be used by ESRI with ArcGIS and distributed together, since the GPL license terms would need to be transferred to ArcGIS too, which is covered by a proprietary license. However, if the library is covered by the LGPL license, then ESRI can use the library and ship both the GIS program and the library to its customers. For a detailed discussion of terms and licenses in relation to free and open source software we refer to Johnson (1999) and the FSF webpages (FSF, 2008b). Steiniger and Bocher (in press) also discuss three common misconceptions of the GPL.

3. GIS and landscape ecology today

3.1. What GIS functions are used in LSE today?

A brief survey of recent Landscape Ecology (LSE) literature provides examples of the typical kinds of tasks that landscape ecologists perform with GIS (Fig. 1). These include (but are not limited to) the use of spatial analysis functions, such as distance measurements (Léonard et al., 2008) and buffering (Öckinger and Smith, 2008), the application of configuration metrics to landscape mosaics (e.g.; diversity and evenness: Concepción et al., 2008), the calculation of single patch metrics (e.g.; area, width, shape index: Renfrew and Ribic, 2008), the derivation of secondary data from digital terrain models, such as slope, aspect (Kellogg et al., 2008), and watersheds (Kennedy et al., 2008), or the detection of change in landscape structure by comparing land-cover classifications for different years (Hall and Hay, 2003).

However, before any data analysis can take place data need to be collected either by field work (e.g. Pocewicz et al., 2008 used a GPS device), by digitising from aerial images (e.g. Arellano et al., 2008), or extracted from satellite imagery by manual or automated/semi-automated feature extraction techniques (see GEOBIA — *GEOgraphic Object-Based Image Analysis* — Hay et al., 2005; Hay and Castilla, 2008). If the data arrive from different sources, data conflation (i.e. integration) may be necessary (Blasby et al., 2002). Additional data creation and editing (i.e. updating) are needed if landscape changes have occurred that are not yet reflected in the available mapping data. If a GIS data archive has been developed and analysis has occurred, then the data and results are typically presented in the form of maps, charts or tables. A strength of GIS includes the rapid creation of maps for the presentation of the research area and different results, which can be based on different scenarios, needs or questions of the same data (see e.g. Bunce et al., 2008; Kellogg et al., 2008).

A further task that may be accomplished with the aid of GIS is *simulation*. For example the simulation of land-use change (Parker et al., 2003), simulations to assess the accuracy of process models (e.g. using Monte Carlo methods: Burrough and McDonnell 1998), or simulations of specific natural disturbances such as forest fire (He and Mladenoff 1999). For simulation models, GIS software typically provides basic

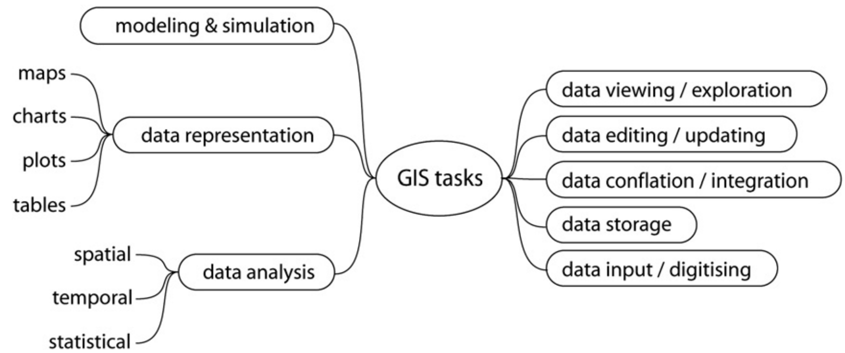

Fig. 1. Tasks that can be accomplished with GIS software. Note, 'charts' refers here to the allocation of bar and pie charts on a background map, while 'plots' (e.g., scatter plot, histogram, etc.) do not need to have a geographical reference.

components for data input/output, analysis, and visualisation, while the (numerical) model itself can be treated as a separate software component. Consequently, simulation models are often developed either on top of the GIS software, i.e., as an integrated module, or GIS and simulation software are used — or coupled — separately.

When we assess the list of key research priorities presented by Wu and Hobbs (2002) for Landscape Ecology, then we identify at least three critical topics where the use of GIS is beneficial or even required: (i) the assessment of scaling effects — GIS provides transformation tools for controlled upscaling/generalisation and the analytical tools for a quantitative evaluation of scaling effects, (ii) data acquisition and accuracy assessment — GIS software provides the necessary tools for data creation and integration, as well as functions to perform accuracy assessments, and (iii) exploring/determining the causes, processes, and consequence of land use and land cover change — GIS software provides the functionality to detect and quantify (multi-temporal) spatial change as well as to create change maps, and more recently, change animations.

3.2. What GI tools and software are used in LSE today?

To answer this question, we analysed the first two issues in 2008 of the journal Landscape Ecology as a reasonable sample of recent LSE research. Our findings indicated a strong bias towards the use of proprietary rather than free-of-cost GI tools. Specifically, we found that in 16 articles that used GIS, software from the company ESRI was used 11 times (i.e. ArcGIS, ArcView, ArcInfo), whereas in the remaining five articles, no reference to the software product was given. Additional mentions of GI tools include ERDAS and an ENVI extension for ESRI products, which provide remote sensing image analysis functionality. One article also reported the use of Patch Analyst (Elkie et al., 1999), a free extension for ArcGIS, and another the use of FRAGSTATS (McGarigal et al., 2002); of which both provide a set of spatial functions and metrics for landscape analysis. Although statistics programs can not be considered as GI tools, we note that the software packages SAS, Statistica, R, Genstat, SPSS, GraphPad and S-Plus have been used in the articles — of which only R is free software.

What other free-of-cost GI tools have been used in landscape ecology? In Table 1 we list a number of free-of-cost GI analysis tools that have specific utility for landscape ecology research. Valuable sources for our search have been www.spatialanalysisonline.com and www.ai-geostats.org.

4. Categories of GI tools useful for LSE analysis

The tasks depicted in Fig. 1 address the basic tasks of management, analysis, modelling, and the presentation of geographical data to assess and monitor the environment. Software that helps to fulfil these purposes has generally been labelled as "Geographic Information Systems" (GIS) (c.f. Longley et al., 2005; Steiniger and Weibel, 2009). However, in addition to a typical (Desktop) GIS that may serve all these purposes at once, a wider range of Geographic Information tools (GI tools) exists that serve only one or a subset of these tasks. In Fig. 2 we present a range of GI tools and software that have utility for landscape ecology and explain these categories in the following paragraphs. Specifically, we will distinguish between a set of core GI tools that are frequently used by landscape ecologists today, and a set of advanced tools that is rarely used today by landscape ecologist, but necessary to consider with respect to future tasks and challenges.

4.1. Core GI tools for LSE research and projects

Based on our previous analysis of the landscape ecology literature (Section 3.1) we identify five categories of core GI tools that are frequently used (either alone or together) in LSE research:

1. Desktop GIS — represented by a typical standalone computer with GIS software — are used for data collection, editing, analysis and presentation (see tasks in Fig. 1). Software companies often distinguish desktop GIS product-lines according to the functionality offered, for example a Viewer (e.g. ESRI's ArcExplorer) is used for data viewing and exploration. An Editor (e.g., ESRI's ArcView and ArcGIS-ArcEditor) is used for viewing, editing and simple data queries, and an Analyst (e.g. ESRI's ArcGIS-ArcInfo) offers advanced spatial and statistical analysis and mapping functions (Steiniger and Weibel, 2009).
2. Mobile GIS (e.g. ESRI's ArcPad) are advantageous for collecting data in the field. Such software often provides specific functions that ease the input of field data, but also functions to integrate location data from GPS devices. In addition to field data and data delivered from organisations such as mapping and environmental agencies, image data from space- and airborne platforms are other important data sources for LSE research (McDermid et al., in press).
3. Remote Sensing Software provides raster processing and analytical functions for image correction, classification, geographic object extraction (Blaschke et al., 2008) and vectorisation (i.e. raster to vector conversion).
4. Software Libraries and extensions can provide basic GIS functionality to be included in other (GIS) software such as methods to show geographic data in different cartographic projections (e.g. the Proj4 library), methods for reading and writing specific geographic data formats (e.g. GDAL/OGR), or functionality for geometric and mathematical calculations (e.g.; GEOS, JTS, JAMA).
5. GIS Extensions denote libraries that deliver additional functionality for a specific software. For example ESRI's ArcGIS Spatial Analyst can be considered an extension that delivers advanced analysis functionality for ArcGIS and the ArcGIS Data Interoperability Extension (which allows for data read/write to and from additional data formats).

Table 1
A non-comprehensive list of free-of-cost GI tools used in the field of landscape ecology from 1995–2008.

Software	Description	Source available	References
Analysis software (Spatial)			
Conefor Sensinode 2.2	To quantify the importance of habitat areas for the maintenance of landscape connectivity.	Yes	http://conefor.org Saura and Torné (2009)
CrimeStat 3.1	Spatial statistical analysis tools for point pattern analysis, e.g. distance analysis, kernel density.	No	Levine (2007)
FRAGSTATS	Calculation of landscape metrics for categorical map patterns.	V2 Yes, V3 no	McGarigal et al. (2002)
GUIDOS	Software for morphologic spatial pattern analysis on raster image data.	No	Vogt et al. (2007)
LandSerf (GIS)	GIS software with focus on visualisation and analysis of surfaces.	No	www.landserf.org Wood (2009)
LEAP II	Tools to explore, monitor, and assess a landscape for its ecological status.	No	www.ai-geostats.org Perera et al. (1997)
SADA (GIS)	GIS software with focus on spatial decision analysis and decision assistance.	No	www.tiem.utk.edu/~sada/
SPRING (GIS)	General purpose GIS and remote sensing software.	No	www.dpi.inpe.br/spring/ Câmara et al. (1996)
SaTScan	Spatial, temporal and space-time scan statistics tools for cluster detection.	No	www.satscan.org Kulldorff (1997)
VARIOWIN	Tools for variogram analysis and modelling.	No	Pannatier (1996)
ESRI ArcGIS extensions			
CMAP CASE	Point analysis functions for crime and animal movement, e.g. dev. ellipses, spider diagrams.	N/A	www.crimeanalysts.net
Hawth's Tools	Tools for data editing, analysis and sampling.	No	Beyer (2004)
Point Analyst 1.0	Functions for spatial sampling and analysis, e.g. point interpolation and similarity assessment.	Yes	Rempel (2003)
Patch Analyst 4.0	Functions for analysis of patches — raster and vector, e.g. calculation of landscape metrics.	No	Elkie et al. (1999), Rempel and Kaufman (2003)
PathMatrix 1.1	Computes matrices of distances among samples, based on a least-cost path algorithm.	Yes	http://cmpg.unibe.ch/software/pathmatrix/, Ray (2005)
STAMP	Functions for the analysis of moving polygons.	No	Robertson et al. (2007)
V-LATE 1.1	Provides most common landscape metrics.	No	Lang and Tiede (2003)
Geostatistics			
ade4	Functions for exploratory analysis of ecological and environmental data in R (a stats' package)	Yes	pbil.univ-lyon1.fr/ADE-4/ Chessel et al. (2004)
geoR	Package for geostatistical data analysis using the R software.	Yes	http://leg.ufpr.br/geoR/ Ribeiro and Diggle (2001)
Gstat	Functions for multivariable geostatistical modelling, prediction and simulation for R/S.	Yes	www.gstat.org Pebesma (2004)
Simulation			
Dinamica EGO	Dynamic modelling software used for urban growth and tropical deforestation studies.	No	www.csr.ufmg.br/dinamica/ Soares-Filho et al. (2002)
HARVEST 6.1	To assess spatial pattern consequences of broad timber management strategies.	Yes	www.nrs.fs.fed.us/tools/harvest/, Gustafson and Crow (1996)
LANDIS 4.0/LANDIS II	Software for simulating landscape change over large spatial and temporal scales through harvesting, wind, fire, etc.	No	www.landis-ii.org He et al. (2005)
Qrule	A program for the generation of neutral models, and testing hypotheses relating process and pattern.	Yes	www.al.umces.edu/Qrule.htm Gardner (1999)
SELES 3.4	A tool for spatio-temporal landscape simulations that integrate natural and anthropogenic processes and to track indicators	No	http://seles.info Fall and Fall (2001)
SIMMAP 2.0	For simulating landscape spatial patterns through the modified random clusters method.	Yes	Saura and Martínez-Millán (2000)
Zoning			
MarXan/SpExAn	Decision support software for conservation planning problems.	No	www.uq.edu.au/marxan/ Possingham et al (2000)

An example of LSE research that uses and incorporates all of these core GI tools is the Foothills Model Forest Grizzly Bear Research Program. This program assesses grizzly bear habitats in Alberta, Canada (Nielsen et al., 2003) and uses the proprietary ArcGIS as its Desktop GIS, and ArcMap for its Mobile GIS. PCI and Definiens are used for Remote Sensing image analysis, and ESRI's Spatial Analyst as well as Hawth's Tools (Beyer, 2004) — two extensions for ArcGIS — have been used for the habitat mapping program.

4.2. Advanced GI tools for large LSE projects

In addition to the previously described core set of GI tools, an advanced set of software are particularly useful for large scale projects. Here, ‘large scale’ refers to the many research groups and institutions involved, and/or a large number and size of the area of interest that typically results in (many) massive datasets that need to be collected, stored and analysed. Such projects often also need to integrate data from different sources and disseminate their results to a wide audience via the web. Because the number of large scale projects that aim to monitor the environment for biological and landscape conservation purposes appears to be growing, the following section briefly provides an overview of these additionally useful GI tools:

- Spatial Database Management Systems (DBMS; e.g. Oracle Spatial 10g, PostGIS), provide functions to manage (i.e. store, query, and process) the vast archives and inventories of spatially referenced data — and/or geographic objects — collected from field work, remote sensing and other data providers. Spatial databases are a preferred alternative to file-based geo-data storage and management if the dataset contains several thousands of geo-objects.
- Web-Map-Servers (e.g.; ESRI's ArcGIS Server, MapServer, GeoServer) provide the possibility to deliver data stored in databases via the Internet or Intranet to (external) users as image and/or vector data. Such web map services are particularly useful to present research results in form of a (dynamic) map to a wider

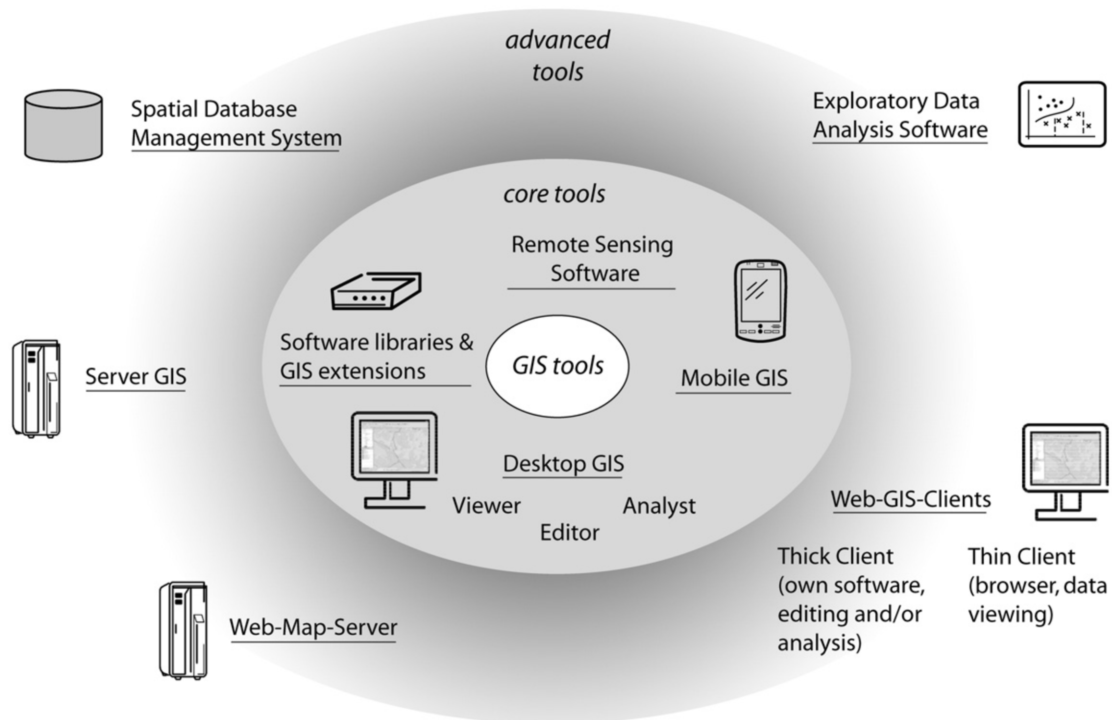

Fig. 2. Geographic information tools for Landscape Ecology.

audience. The (external) user will need either a 'thin client' or a 'thick client' to view and query the data in interaction with the web map server. A *Thin Client* is typically a simple web browser with which Google Maps or Microsoft Bing Maps can be accessed. *Thick Clients* are typically desktop GIS (e.g.; ESRI's ArcExplorer, ArcGIS ArcView); however the Google Earth application can also be considered as a thick client. In comparison to thin clients, which often provide only viewing and query functionality, thick clients can offer additional functions for data creation, editing, and analysis.

- Server GIS (e.g. ArcGIS Server) provide essentially the same functionality as desktop GIS but allow users to access this functionality via networks, i.e. Intranet or Internet (Burghardt et al., 2005). Usually a thick or thin client is used to display data and access the analysis tools provided by the GIS server. This is exceptionally useful for multiple geographically distributed research groups working on or contributing to a common project, each of whom can access the local server software and data across the network as if it were local.
- Exploratory (spatial) data analysis tools (e.g.; GeoVISTA Studio, GeoDa) provide functions to explore, describe and visualise spatial, statistical and temporal data. In particular, such software offers a variety of visualisation methods, such as parallel coordinate plots, scatter plots, box plots and different thematic map creation methods (Anselin et al., 2006). These functions can be used to generate different perspectives of the data and to browse massive data archives for regular patterns as well as for unusual "events" (i.e. outliers).

To identify all the freely available GI tools that can be assigned to the categories above is beyond the scope of this paper, as the webpage www.opensourcegis.org lists more than 200 GIS related projects alone. Therefore, we will restrict our analysis to a limited group of key FOS desktop GIS that provide functionality useful for landscape ecology. However, for the interested reader we also provide additional examples of free software for select LSE applications (see Appendix A/Table 5).

5. Eight free and open source desktop GIS

Based on a survey of the Internet we have identified eight FOS desktop GIS (Table 2) that are (i) suitable for GIS tasks in LSE, and (ii) that have achieved a mature development stage, so as to provide sufficient GIS functionality for data creation, editing, and analysis:

(1) GRASS GIS is possibly the most well-known GIS in the LSE community, (Neteler and Mitasova 2008) due in part to its maturity and long existence. In addition, the possibility to couple GRASS with the statistic software R and the implementation of landscape metrics in the *r.le* package (Baker and Cai, 1992; Baker, 2001) have contributed to its frequent use.
(2) Quantum GIS (or QGIS, Hugentobler, 2008). From a technical perspective, QGIS is considered as one of the most promising free desktop GIS, because it (i) provides an effective interface to (the sometimes difficult to use) GRASS GIS, and (ii) it offers good customisation possibilities (e.g. Python as scripting language). Currently the software project has one of the largest FOS GIS user communities.
(3) ILWIS (or ILWIS Open) exists almost as long as GRASS GIS. It is a mature GIS that not only encompasses a wide range of vector and raster processing functions but also a suite of image processing functions that are usually only available in remote sensing software.
(4) uDig's GIS functionality is more focused towards data viewing and editing from databases and Internet sources. However, it has recently been extended for applications in forest management (a proprietary application) and biodiversity.
(5) SAGA GIS has been developed for applications and research in physical geography. Hence SAGA's strengths are functions for (raster) analysis and visualisation of terrain data.
(6) OpenJUMP is a GIS that has been developed particularly for vector data editing and conflation. The strong set of vector drawing and editing functions is currently enhanced by functions for the analysis of vector datasets by a group of volunteers.

Table 2
8 major free and open source desktop GIS suitable for landscape ecology tasks (see also Table 3).

GIS project (founding year)	Webpage	User focus[a]	Data focus[b] (raster vs. vector)	Platform	
				Operating systems	Language
GRASS (1982)	grass.osgeo.org	Experienced,…, research	More raster	MS-Windows, Linux, MacOSX	C, Tcl/Tk, Python
Quantum GIS (2002)	qgis.org	Novice,…, research	More vector	MS-Windows, Linux, MacOSX	C++, Qt4, Python
ILWIS Open (1984/5)	ilwis.org	Novice,…, research	Raster and vector	MS-Windows, Linux	MS Visual C
uDig (2004/5)	udig.refractions.net	Novice,…, research	More vector	MS-Windows, Linux, MacOSX	JAVA
SAGA (2001/2)	saga-gis.org	Novice,…, research	More raster	MS-Windows, Linux	MS Visual C
OpenJUMP (2002/3)	openjump.org	Novice,…, research	Vector	MS-Windows, Linux, MaxOSX	JAVA
MapWindow (1998)	mapwindow.org	Novice,…, research	Raster and vector	MS-Windows	MS Visual Studio .Net
gvSIG (2003)	gvsig.gva.es	Novice,…, research	More vector	MS-Windows, Linux, MaxOSX	JAVA

[a] User levels: (i) novice (viewing), (ii) experienced (editing, simple analysis), (iii) expert (analysis), (iv) research (scripting, programming).
[b] Data focus: subjective evaluation with respect to (i) software history and (ii) number of functions for raster and vector data editing and analysis.

(7) The MapWindow GIS project (Ames et al., 2007) evolved from a different perspective than the previous desktop packages. The original aim was not to develop a desktop GIS but rather a library that provides a basic set of GIS functions for customised software development. However, MapWindow GIS extensions now provide more than the necessary basic functionalities of a desktop GIS and also offer a suite of functions for hydrologic analysis (see Tables 3 and 4).
(8) gvSIG development is funded by the regional government of Valencia (Spain) to replace proprietary GIS software of ArcView functionality in administration (Alfaro and Rico, 2005). With development undertaken together with universities, a number of scientific extensions for GIS analysis are currently being built, such as a connection to the Sextante library, which provides terrain analysis and geostatistic functions (Olaya, 2008).

Several other software with GIS functionality were not considered in this core list (Table 2). These include, OrbisGIS, Kosmo, TerraView and Kalypso. OrbisGIS was omitted as this software has not yet reached a mature stage (Steiniger and Bocher in press). Kosmo was excluded as its developers and users are primarly Spanish speaking, and its manuals are available in Spanish only (Steiniger and Bocher in press). We found the same, i.e. a Spanish language focus, for TerraView which provides a GIS front–end to access the analysis functionalities of the TerraLib software library (Câmara et al., 2008). Due to the documentation being in Spanish only, we haven't been able to evaluate both software products. However, we encourage Spanish speaking readers to consider both GIS due to their active user and developer communities. Although the software Kalypso (kalypso.bjoernsen.de) offers some GIS functionality, we did not include it, since it has a special application focus on hydrology related modelling and simulation, such as flood, risk and evacuation modelling.

6. Comparing the eight FOS desktop GIS with proprietary GIS

From a LSE perspective this section will compare free GIS software with proprietary software with respect to (i) functionality provided by the software, (ii) development and distribution models, (iii) software documentation and user support, and (iv) user restriction and freedoms that emerge from the applied software licenses.

6.1. Analysis and comparison of functionality

6.1.1. General functionality

Initially we investigated how the 8 desktop GIS listed in Table 2 can be used for the GIS tasks that are typically carried out in LSE (see Fig. 1). The results of that evaluation are summarised in Table 3 and select components are discussed below. In general, each of the 8 free desktop GIS provides the necessary functionality to fulfil the full range of basic GIS tasks in LSE, from data viewing to spatial analysis (Table 3). However, with respect to standard functionality we note that a general weakness with current FOS desktop GIS (except GRASS) is the lack of tools for the creation of professional-style maps with output quality comparable to ArcGIS. However, most of the 8 desktop GIS provide basic plotting and screen-shot functionality so that with the help of additional layout and drawing software it is relatively simple to create maps and illustrations for scientific publications (e.g. free layout software: GIMP — www.gimp.org, Inkscape — www.inkscape.org; or proprietary software: Adobe Photoshop and Illustrator — www.adobe.com).

Table 3
Support of GIS tasks by different desktop GIS[a].

Task	GRASS	QGIS	ILWIS	uDig	SAGA	Open JUMP	Map Window	gvSIG	Arc View 9.3[e]
Viewing/exploration	●	●	●	●	●	●	●	●	●
Creation/ digitizing	●	●	●	●	●	●	●	●	●
Editing/updating	●	●	●	●	●	●	●	●	●
Conflation/integration	●			●		○			
Presentation									
Maps	●	●	●	●	●	●	●	●	●
Charts[b]	●	●	●		●	○			●
Plots[c]	Via R	●	●		●	○			●
Tables	●	●	●	●	●	●	●	●	●
Overlay analysis									
Raster	●	Via GRASS	●	Via JGrass	●	Via Sextante	●	Via Sextante	
Vector	●	●	●	●	●	●	○	●	Partly
(Spatial) statistics	Via R		●	Via JGrass	●	Pirol- JUMP	Raster only	Via Sextante	●
Customization (script or API[d])	API, Python, Perl	API, Python	ILWIS scripts	API, Groovy	API, Python	API, Jython	API (.Net)	Jython	Python and others
GPS data import	●	○	●	○	●	○	●	gvSIG Mobile Pilot	●

[a] ● Functionality provided, ○ functionality provided by software plugin (i.e. an extension). See also www.spatialserver.net/osgis/ for details.
[b] Charts: i.e. a thematic map that shows bar charts, pie charts, and graduated symbols.
[c] Plots: scatter plot, bar plot, histogram, etc.
[d] API: Application Programming Interface — a possibility for custom function development which enables tasks such as simulation and modelling.
[e] ESRI ArcGIS ArcView 9.3: we only assessed the standard functionality and not functionality that comes with extensions that require additional purchases.

Table 4
Landscape related analysis applications of free and open source desktop GIS.

Desktop GIS	Known LSE-analysis relevant GIS extensions	Known LSE relevant applications	Literature references for applications
GRASS[a] (1982)	r.le (now: r.li), [1], interface to R [2] and gstat[3], AniMove[10]	Landscape metrics [1], terrain analysis [3], hydrologic analysis [3], geostatistics [3], solar radiation modelling [4], flood management [5], LiDAR data processing [6], habitat analysis [7], …	[1] Baker (2001), [2] Bivand (2007), [3] Neteler and Mitasova (2008), [4] Suri and Hofierka (2004), [5] Garcia (2004), [6] Brovelli et al. (2004), [7] Tucker et al. (1997)
QGIS (2002)	eVis[8], ftools & manageR [9], AniMove [10], raster algebra plugin [11], QGIS provides an interface to GRASS modules	Event visualisation [8], animal movement analysis [10],	[8] Ersts et al. (2007), [9] Farmer (2008), [10] www.faunalia.it/animov/, [11] Rowlingson (2008)
ILWIS[a] (1984/85)	– No extensions –	Terrain analysis [12], geostatistics [13], habitat suitability [13], solar radiation mapping [15], land management [16], …	[12] Hengl et al. (2003), [13] Nijmeijer et al. (2001), [14] Kushwaha et al. (2004), [15] Kandirmaz et al. (2004), [16] Zhou (1995)
uDig (2004/5)	DIVA-GIS [17], JGRASS [18], Axios, uDig Extensions [19],	Biodiversity data analysis [17], terrain analysis [18], hydrologic analysis [18], forest management terrain analysis [21][22], geostatistcs [21], solar radiation	[17] CIP (2008), [18] www.jgrass.org, [19] www.axios.es
SAGA (2001/2)	Interface to R [20]	modelling [21], water quality assessment [23], plant diversity assessment [24]	[20] Brenning (2008), [21] Olaya (2004) [22] Brenning and Trombotto (2006) [23] Lado et al. (2008) [24] Klimek et al. (2007)
OpenJUMP (2002/3)	OpenJUMP Pirol, Edition [25], Landscape, Pattern Extension [26], SEXTANTE[33]	Precision farming (Pirol Project)[25], nature conservation and farm management [27], ecologic data exploration [28], pattern extraction [26], map generalisation [26],	[25] Brüning et al. (2007), Kielhorn and Trautz (2007), [26] Steiniger (2008), [27] Vogel et al. (2007), [28] Zhang et al. (2007)
MapWindow (1998)	TauDEM [29], BASINS [30], WaterBase [31], Bayesian Analysis Plugin[32]	Terrain analysis [29], hydrologic analysis and modelling [29][30], water (quality) management [30][31]	[29] Tarboton (2008), [30] www.epa.gov/ost/basins, [31] George and Leon (2007), [32] Ames and Anselmo (2008)
gvSIG (2003)	SEXTANTE [33], Raster Pilot [34], Network Pilot [34], Dielmo Open LiDAR [34], gvSIG mobile Pilot[b] [34]	Terrain analysis [33], geostatistics [33],	[33] Olaya (2008), [34] www.gvsig.gva.es

[a] We present only selected references for GRASS and ILWIS.
[b] gvSIG Mobile Pilot is a mobile (light) software version intended for field work.

To compare the functionality of the 8 FOS GIS with those of proprietary GIS we evaluated the capabilities of ESRI's ArcGIS in the ArcView edition. ArcGIS was selected for the comparison as this product was highly reported in the LSE articles that we previously assessed (see Section 3.2). When ArcView functionality is compared with the free GIS in Table 3, we observe that the FOS GIS generally provide similar functionality as proprietary desktop GIS at the lower level of the functionality spectrum (i.e. GIS Viewer & Editor software, and not GIS Analyst software). Since most of the FOS desktop GIS have a special application focus, some provide more functionality to accomplish one task, while providing fewer functions for others. For instance GRASS and SAGA are strong in raster analysis and are able to compete with high-end proprietary GIS (e.g. ArcInfo), while also having less user-friendly, or fewer vector graphics drawing and editing functions. In contrast, OpenJUMP and gvSIG provide strong vector editing and analysis tools, and offer only few, or no built-in raster analysis tools.

Interestingly, this focus on certain GIS tasks by the free software projects has resulted in an open-minded and flexible FOS GIS user community that chooses the best software for each task to accomplish. This might be found cumbersome by some, but it ensures that research is not limited by the functionality provided by one particular software and also results in a well skilled user community that understands the underlying principles and not only “presses buttons”.

6.1.2. Comparing functionality with respect to special needs of the landscape ecologist

Whereas the previous section focused on general GIS tasks carried out by landscape ecologists it is also worth to analyse the functionality of free and proprietary GIS with respect to particular needs. We considered here three categories: (i) the need for advanced GIS analysis functions (e.g. DEM analysis, spatial auto-correlation, etc.), (ii) the need for GIS in field work, and (iii) the coupling and use of GIS for simulation purposes.

- Advanced GIS Analysis: Spatial and spatio-statistical analysis functions that are non-standard but of interest for the LSE community are usually not contained in standard proprietary software. However, software manufacturers often include such functions in more expensive high-end versions of GIS (e.g. ArcGIS of ArcInfo level) or offer them in the form of software extensions that need to be paid for separately (e.g. ESRI's Spatial Analyst). The situation for the FOS desktop GIS is different. For some there exist advanced analysis tools, while for others there doesn't. If the functionality exists, then it is also often provided via extensions. To present a better picture of this situation we searched for particular FOS GIS software extensions, and we also evaluated articles that report on applications that are related to LSE. The results of this evaluation are summarised in Table 4.
  The two application areas that we identified most often in our FOS GIS application survey and that are of primary relevance to LSE research are (i) terrain analysis and (ii) geostatistics. Applications for the analysis of habitats, solar radiation modelling, map generalisation, and biodiversity assessment can also be found. In addition, several FOS GIS have been used for management applications that include water, forestry, and precision farming.
  With respect to the need for GIS statistical functions in LSE, ranging from hypothesis tests to plotting tools for data exploration (see Section 3), Table 3 and 4 shows that FOS desktop GIS have

limitations. Specifically, only ILWIS provides a large set of integrated statistic functions. However, it can be noted that GRASS and SAGA do offer the possibility for a loose coupling with the R statistics package (Bivand 2007; Brenning 2008). We also note that if data exploration functions were required, we would recommend using Exploratory Data Analysis (EDA) tools, such as GeoDa and GeoVista (see Table 5).

- Mobile GIS for Field Work: GIS software for field use is considered as separate product by GIS software companies. Consequently, they must be purchased extra. On the FOS GIS side there is currently a lack of mobile GIS software. Although there have been experiments with GRASS on a PDA (Neteler and Raghavan 2006) and with OpenJUMP running on a tablet PC, the desktop GIS currently provide no additional functionality to facilitate fieldwork (other than GPS data integration). The only exception is the GIS software gvSIG Mobile Pilot, which was first released in March 2008.
- GIS for Simulation: Nine years ago Câmara et al. (2000) noted that new simulation and modelling techniques developed in computer

Table 5
Free-of-cost GI tools and software useful for research in landscape ecology, not listed in Tables 1 and 2.

Software	Short description	Source code available	Website
Spatial DBMS			
MySQL (with spatial Extender)	Relational database management system	Yes	www.mysql.org http://forge.mysql.com/wiki/GIS_Functions
PostGIS for PostgreSQL	PostGIS adds support for geographic objects to the PostgreSQL object-relational database	Yes	http://postgis.refractions.net
Web Map Server			
GeoServer	Two platforms fro publishing spatial data and interactive mapping	Yes	www.geoserver.org
MapServer	Applications to the web, including data editing capabilities	Yes	www.mapserver.org
Explorative Data Analysis software			
GeoDa	Software for spatial data analysis, geovisualization, spatial autocorrelation and spatial modelling	No	http://geodacenter.asu.edu/software
GeoVISTA Studio	An environment designed to quickly build applications for geo-computation and geographic visualization	Yes	www.geovistastudio.psu.edu
STARS	Software for space-time analysis of regional systems	Yes	http://regionalanalysislab.org/index.php/Main/STARS
Libraries			
GDAL/OGR	Data format transformation libraries – GDAL for raster formats, OGR for vector formats	Yes	http://gdal.osgeo.org
Generic Mapping Tools	A package with command line tools that allows creation of maps.	Yes	http://gmt.soest.hawaii.edu/
JAMA and GNU Scientific Library	Two libraries that provide mathematical functions	Yes	http://math.nist.gov/javanumerics/jama/ http://www.gnu.org/software/gsl/
JTS Topology Suite/GEOS/NetTopologySuite	Geometry libraries — provide vector geometry types (Point, Line, Area) and functions such as intersection models, buffer, centroid, convex hull etc.	Yes	http://tsusiatsoftware.net/jts/main.html http://geo.osgeo.org
LUPOLib	Zoning library — methods to optimize land-use pattern for maintaining ecosystem function	Yes	http://www.ufz.de/index.php?en=4302
OpenBugs	Statistic library — for Bayesian analysis of complex statistical models using Markov chain Monte Carlo (MCMC) methods	Yes	http://mathstat.helsinki.fi/openbugs/
Sextante	DEM analysis toolset — with functions for map algebra, hydrologic analysis, terrain analysis, geostatistics, etc.	Yes	http://forge.osor.eu/projects/sextante/
TerraLib	A Spatial DBMS that also provides spatial and spatio-temporal analysis functions including CA	Yes	www.sextantegis.com/en/ http://www.terralib.org/
Multi-Agent Simulation packages (see also www.spatialanalysisonline.com)			
MASON		Yes	http://cs.gmu.edu/~eclab/projects/mason/
Repast Simphony	Three agent-based modelling toolkits that simplify model creation and use	Yes	http://repast.sourceforge.net/
SWARM		Yes	www.swarm.org
NetLogo	Multi-agent programming language and integrated modelling environment	No	http://ccl.northwestern.edu/netlogo/
(Open-)StarLogo	Agent-based simulation language an extension of the Logo language	Yes	http://education.mit.edu/openstarlogo/
OBEUS	Agent-based environment for urban simulation	No	http://www.tau.ac.il/~bennya/research1.html
Remote Sensing Software			
CHIPS	Image processing and spatial data analysis software with extensive support for AVHRR data	No	http://www.geogr.ku.dk/chips/
InterImage	A knowledge based framework for automatic image interpretation	Yes	http://www.lvc.ele.puc-rio.br/projects/interimage/
MultiSpec	Software for analysis of multispectral and hyperspectral image data	No	http://cobweb.ecn.purdue.edu/~biehl/MultiSpec/
OSSIM	Image processing software for remote sensing, photogrammetry and GIS	Yes	www.ossim.org
GIS			
Forestry GIS	Shapefile editing program, digitizer and GIS data query tool for Windows	No	http://www.forestpal.com/fgis.html
SavGIS	Full (French) GIS on GIS analyst level	No	www.savgis.org
Miscellaneous			
PCRaster	Language for construction of iterative spatio-temporal environmental models	No	http://pcraster.geo.uu.nl
SANET	Package for spatial analysis of networks	No	http://ua.t.u-tokyo.ac.jp/okabelab/atsu/sanet/
S-Distance	Spatial decision support system, mainly focusing on location–allocation analysis	No	http://www.prd.uth.gr/res_labs/spatial_analysis/software/SdHome_en.asp
TAS	Terrain Analysis System — providing functions for geomorphologic and hydrologic analysis	No	http://www.uoguelph.ca/~hydrogeo/TAS/

science and GIScience have rarely made their way into proprietary GIS software. This fact remains today. To date, we have found very few proprietary GIS that offer out-of-the-box simulation functionality such as optimisation methods, agent-based models, or cellular automata. Though we do note that a cellular automata and a neural network model are available in IDRISI, and ESRI's ArcGIS will contain an optimisation tool in the future. This situation is similar for free GIS — i.e. there have been only few attempts to integrate/couple FOS GIS with simulation software. For instance Lake (2001) developed MAGICAL, a multi-agent modelling extension for GRASS, and Zhang et al. (2008) present an agent simulation that utilises QGIS. However, both works are not explicitly related to ecological applications. To our knowledge an integration of GIS and simulation functions is only provided by the spatial data management system TerraLib (Câmara et al., 2008, see Table 5 for additional agent software).

This last issue as well as the lack of integrated statistics functions can be viewed as a temporary weakness, since the majority of the 8 FOS GIS projects are relatively young (e.g., QGIS: 2002; MapWindow: 1998; gvSIG: 2003). If one considers the time needed to obtain a stable and mature platform (typically 2–3 years), as well as the time needed for research and publication (2 years), one can not expect to find a multitude of advanced spatial analysis functions and research applications in the literature. Thus, we expect especially for these younger projects that their popularity and with them their user and developer communities as well as (research) application reports will grow over time.

6.2. Comparing development and distribution models

In FOSS projects, developers are often located all over the world, thus direct communication is sometimes difficult and time consuming. An approach that mitigates several software development problems is to modularise software; that is, to make several logical parts independent from each other (so-called components or libraries). FOS GIS projects most often use this model, which results in one or several core libraries that contain the most important functions (e.g. data input and output, geometry and feature model, user interface classes, etc.) and additional libraries that are built on top of these core libraries and that provide the final GIS functionality. This model is applied by GRASS, QGIS, MapWindow, gvSIG, uDig and OpenJUMP, and it allows for the distribution of a basic application that contains core GIS functions; whereas advanced or special GIS functionality can be delivered via so-called *plug-ins* and *extensions*. Note that an extension usually contains several plug-ins. This plug-in-centric strategy can be cumbersome as the user needs to first explore what plug-ins are available. However, it also facilitates the development of specialised functions by external developers.

One particularly positive application example of the plug-in-model is the Sextante library (Olaya, 2008). This library currently provides a set of terrain analysis functions that can be plugged-in into gvSIG and OpenJUMP. The library is maintained and distributed by an independent developer team of terrain analysis specialists. This way (i) the implementation of algorithms can be done by experts in a particular field — which should result in correct functionality, (ii) the algorithms can be used in several GIS (as the source code is open), and (iii) the desktop GIS core developers do not need to be bothered with an integration into the GIS core software for subsequent distribution.

For the FOS GIS SAGA and ILWIS we could find none, or only few additional plug-ins/extensions as summarised in Table 4. If these GIS are downloaded one obtains a version that contains all available functions at once. The reason might be that these FOS GIS are older, and thus, different development models have been applied when they were first developed. However, we note that these GIS projects have also started to implement mechanisms that allow for plug-in development.

For many years, proprietary GIS have offered ways to customise software in terms of adding functionality or performing batch processing. This was often done by the use of scripting environments (e.g. ArcView Avenue, ArcInfo AML, or MicroStation MDL). However, these environments rarely allow access to the core software functions (the source code is closed), but instead provide access to higher-level (i.e. abstracted) functions. As a result, the software remains a black box. Lately, the plug-in strategy has also been adopted by proprietary GIS manufacturers too. For instance Fragstats and Patch Analyst for ArcGIS are two examples that use the plug-in concept.

Finally, we note that there is a certain level of programming skills required to customise software that may be beyond the skill-set of most landscape ecologists. Though this holds true not only for the development of new functionality in FOS GIS but also for proprietary GIS.

6.3. Comparing documentation and user support

6.3.1. Documentation and general support

Proprietary software are usually delivered with a manual that explains all the inherent functionality. Extra training courses are also offered to provide a guided introduction into the software, or to learn how to use the software for a particular application. If user communities have a certain size then additional user books may be available. The same can be said of the FOS software. However, we found that some FOS GIS projects have documentation only available online, or that the documentation of new features is delivered months after the initial software release. This is partly reasoned by a lack of volunteers that are willing to help with documentation. Another general issue can be a lack of usability. Whereas some FOS desktop GIS allow for creation and editing of data in a straight forward way (e.g. OpenJUMP), it is necessary for users of other GIS (e.g. GRASS) to consult the documentation if one works with the software the first time. Both these points, i.e. a (possible) lack of usability and the need for documentation, show that it takes time to learn the functionality and potential of FOS GIS software. Whereas free software comes at no license cost, costs in terms of training time have to be accounted for. However, this will be necessary for any new (GIS) software, proprietary or FOS.

In addition to the availability of professional support offered by companies, the support offered by the user and developer community plays an important role for FOS GIS. While companies offer training and hotline support for a fee, the FOS GIS communities provide help and feedback via free email lists, forums and wikis. If questions are not too specialised, average response times are typically within one or two days, but also responses in 1–2 hours are possible.

6.3.2. Technical support

Whereas the previous section addressed general support in terms of user help, in this section we address user requests to technical support e.g., user requests to add software functionality and version compatibility (i.e. data saved with ArcGIS version 9.x should still be readable with version 10). A problem that occurs for research and small user communities is a lack of official vendor support simply because these communities do not generate large profits for a software company compared to users that need GIS for utility management and business analysis (see also Rey, 2009). If new models and tools are developed for proprietary GIS, then the chance that these tools make their way into the official software is very small. The only option to spread useful tools is to use customisation options such as plug-in systems and scripts.

However, changes to, or the loss of support for such script languages (e.g. for ESRI's ArcView Avenue language and Visual Basic 6), can make such community developed toolboxes worthless, yet they require a significant initial investment to incorporate within the customisation model (e.g. Python for ArcGIS). An example of this is the case of the USGS Animal Movement Extension that was programmed in Avenue, which is no longer supported in ESRI's ArcGIS products. A similar situation occurred to the developers of the Patch Analyst extension for ArcView/

ArcGIS (Rempel, 2008). Developing custom functionality for FOS GIS instead of proprietary GIS provides a reasonable alternative because the source code is accessible. In this case, a loss of official support will not be as critical, because one can program the necessary adaptations oneself to gain (script/plug-in) support again, or contract software developers to implement the adaptations.

6.4. Comparing user freedoms

Proprietary software licenses impose several restrictions on the use of software. Typically, the license does not allow users to distribute the software, e.g. to install it on a second computer at home or to give it to others. The licenses often also prohibit a reverse engineering of the software and modifying of the software (if that is possible at all — as it is rare that the source codes are available to the customer). If the source code is not available, then it is not possible to study how algorithms are implemented and it is not possible to improve the software, i.e. the algorithms.

As outlined in Section 2, Free and Open Source Software (FOSS) licenses, such as the GPL and the LGPL, explicitly allow users to study, modify and re-distribute software. Consequently the following three benefits of FOSS (among others) have been identified (Steiniger and Bocher, in press): (i) FOSS avoids 'reinventing the wheel', (ii) in terms of the source code, FOSS provides the best 'documentation' available, and (iii) users can adapt the software to their own needs without restrictions. All three points are essential for research, when considering that (a) research should not be limited by the functionality that is provided by the software, (b) research experiments need to be repeatable and reproducible, and (c) research can progress faster when models can be analysed, validated, and improved directly, i.e. based on source code, without the problem of misinterpretation, as may be the case when knowledge is obtained/interpreted from articles.

In addition to these general research advantages, the use of FOSS licenses can enhance LSE education and knowledge transfer, particularly in developing countries that don't have the (financial) resources. For example (i) students and researchers can freely and legally download the software and study how LSE models and algorithms are implemented. (ii) LSE researchers worldwide can directly test and adopt new LSE theory and models for different landscapes, ranging from the Siberian tundra to the Brazilian rainforest (Castilla et al., 2009). (iii) Finally it benefits society in general, as the use of free software licenses can facilitate the application of new technologies and knowledge that enables a sustainable use of resources (see also Jolma et al., 2008b).

When talking about FOSS licenses one should also be aware that there will be a loss of intellectual property, because algorithms implemented in FOSS are not patentable. However, we emphasise that the algorithms are still covered by the author copyright that allows personal re-use in other (proprietary) software. For some researchers such loss of intellectual property may matter; but one should recognise also the advantages in terms of disseminating knowledge (i.e., consider how many literature references there are to McGarigal et al., 2002, for developing Fragstats) and the possibility for others to build directly on existing knowledge (even if it is only by using the software). Furthermore, most of the research is financed by public grants; consequently, authors would be returning to the society that supported their research.

7. Conclusions

GIS is an indispensible tool for conducting modern landscape ecology research. However, current proprietary software licenses, pricing and development models limit access to broader community growth and implementation, especially in developing nations. To mitigate these challenges we advocate the use of Free and Open Source (FOS) GIS software for landscape ecology research, and present this article as a starting place for achieving this objective. To facilitate this, we begin by providing a historical perspective of the FOS movement, we then review how landscape ecologists typically use geographic information (GI) tools, then we evaluate eight free desktop GIS with respect to their utility in LSE and compare them with proprietary GIS software. We also provide a summary of numerous related landscape analysis FOSS applications, and extensions that are beyond the scope of this paper, but may be of utility to practitioners.

We report that due to the relative youth of the eight evaluated FOS GIS projects, they generally tend to have less overall GIS functionality than proprietary high-end GIS. Further perceived disadvantages are a limited integration of statistic tools, and a loss of intellectual property by disclosing code. However, on the positive side they all provide the basic GIS functions needed in LSE; they are easy to customise; a growing number of specialised functions and plug-ins already exists for specific LSE applications; and there is a growing community of practitioners willing to freely share their ideas, code and expertise. The development of landscape indices by Baker and Cai (1992) for GRASS GIS is a good example that illustrates how the implementation of algorithms and models in FOS software supports the free spread of knowledge and allows other researchers to study and modify models and algorithms in detail, compared to more closed systems typically found in proprietary software. By developing in GRASS, these scientists also enabled others to (easily) repeat (and build upon) their experiments — a fundamental principle of scholarly research. The example provided by McGarigal et al. (2002) illustrates how disclosing their intellectual property related to the Fragstats algorithms, have ensured the world-wide dissemination and recognition of their code and ideas.

Based on these ideas, we openly invite the landscape ecology community to actively examine the free and open source GIS projects referred to in this paper. We also recommend that this community considers directing their efforts towards a common software development effort within one (or two) FOS desktop GIS, and establishing specific user and developer forums for these projects. We suggest that an ideal location or repository for such development activities would be the IALE website with links to special interest groups who could concentrate on specific research related plug-ins. If such unified software development and research efforts could be initiated then we see great potential to accelerate landscape ecology research world wide.

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Appendix A

In Table 5 we provide an additional selection of software tools that have been mentioned in the text that we found to be useful for research in landscape ecology.

List of acronyms and terms

- API — Application Programming Interface — a possibility for custom function development which enables tasks such as simulation and modelling;

- ARPANET — Advanced Research Projects Agency Network, the predecessor of the Internet was operational in the early 1970's;
- AT&T — American Telephone & Telegraph Corporation;
- CA — Cellular Automata, a grid of cells used to simulate (spatial) processes by application of a set of rules to every grid cell;
- DBMS — Data Base Management System;
- EDA — Exploratory Data Analysis;
- ESRI — Environmental Systems Research Institute www.esri.com;
- FOS — Free and Open Source;
- FOSS — Free and Open Source Software;
- FSF — Free Software Foundation;
- GNU — 'GNU's Not Unix', a recursive acronym — a caricature of the wildebeest/gnu is often used as logo for the GNU project;
- GPL (GNU GPL) — General Public License;
- GPS — Global Positioning System (referred originally to the NAVSTAR GPS);
- GRASS — Geographic Resources Analysis Support System;
- Groovy — an object-oriented programming language for the Java Platform;
- GUI — General User Interface;
- gvSIG — Generalitat Valenciana, Sistema d'Informació Geogràfica;
- IBM — International Business Machines Corporation;
- ILWIS — Integrated Land and Water Information System;
- Jython — an implementation of the Python programming language written in Java;
- LGPL (GNU LGPL) — Lesser (or Library) General Public License;
- MAS — Multi Agent System;
- open source code — meaning that everyone had access to the *un-compiled* text version of the code which could be changed by a user, vs. a *compiled* binary version which could not.
- OpenJUMP — Open Java Unified Mapping Platform;
- PDA — Personal Digital Assistant;
- Python — a (free) general-purpose high-level programming language;
- Oracle — a proprietary database software provider www.oracle.com
- Qt4 — a cross-platform application development framework, widely used for the development of GUI programs;
- SADA — Spatial Analysis and Decision Assistance;
- SAGA — System for Automated Geo-Scientific Analysis;
- Source Code — refers to the original text form of a computer program
- Tablet PC — a laptop or slate-shaped mobile computer equipped with a touch screen or graphics tablet;
- Tcl/Tk — Tool Command Language; a scripting language. Tk refers to a GUI toolkit;
- uDig — user friendly Desktop Internet GIS.

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