

Free GIS for herpetologists: free data sources on Internet and comparison analysis of proprietary and free/open source software

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Abstract. Geographical Information Systems (GIS) have been used widely in zoology and ecology, particularly in herpetology. The use of spatially explicit analysis has increased during the last decade, with the consequent expansion of GIS application in ecology. During the last years, geo-information technology has been developed within the Free/Open Source Software (FOSS) community, resulting in new open source formats and several GIS packages. However, proprietary packages seem still to be the first choice for herpetologists, thus involving non negligible costs for GIS technology adoption. Additional costs arise from environmental data, which are usually expensive, worsening in the case of large study areas. An alternative solution is to use freely available data, despite a possible decrease of resolution. In this review, we aim to show the feasibility of spatial analysis within FOSS GIS packages, rank these packages using the number of available tools and list several data sources freely available on the Internet. We listed several websites providing the most important free data for spatial analysis, i.e. altitude and derived data; past, current and future climatic series data; and satellite derived data. We provide also a list of the most commonly used functions in GIS analysis and their availability in the six software compared in this study (ArcGIS; gvSIG; ILWIS; Quantum GIS; GRASS; and DIVA-GIS). The software gvSIG is the one with more functions (106) followed by Quantum GIS with 94 and GRASS with 84.

Keywords. Geographical Information System, Free/Open Source software, Internet data sources, Herpetology.

INTRODUCTION

A Geographical Information System (GIS) is a specific type of information system, i.e., a set of processes, executed on raw data through observation, measurement, description,

explanation and forecasting, to produce new information useful in decision-making. Some authors extend the scope of the GIS definition from a simple Geographical Information System to a broader Geographical Information Science (e.g., Longley et al., 1991). GIS differs from other information systems because it uses geographically referenced data (Maguire, 1991; Sillero et al., 2002). Commonly viewed as a simple software package, GIS is in fact an integrated collection of software, hardware and people (Sillero et al., 2002). Although other computer programs can use spatial data (e.g., Computer-aided design or CAD and some statistics packages), GIS can perform spatial operations. In fact, any CAD is able to perform geometrical operations in a Cartesian space, using the same entity-attribute model as in GIS vector data, but the user is not compelled to operate in a geographical datum and coordinate reference system context. Moreover, a “non-geographical” spatial information system is completely unable to deal with angular positioning systems (i.e., latitude and longitude data in degrees). The dissemination of GIS occurred after the 70s with small programs that could handle and operate with spatial data and during the 80s with packages like ArcInfo or GRASS, the seeds of the most widely used software nowadays (Longley et al., 1991).

The application of GIS covers a great diversity of fields, such as geography, agriculture, economics, photogrammetry and surveying. Furthermore, GIS has been used widely in zoology and ecology, particularly in herpetology. For example, GIS is an essential tool for producing herptile chorological atlases (Sillero et al., 2002, 2005; Loureiro and Sillero, 2008). In fact, the last herpetological atlases published in Europe used GIS to store, analyse and map species distribution data: e.g., Spain (Pleguezuelos et al., 2002), Italy (Sindaco et al., 2006), Western Palearctic (Sindaco and Jeremcenko, 2008), or Portugal (Loureiro et al., 2008). Gasc et al. (1997) were pioneers on the application of GIS to map species distributions, creating the first herpetological atlas of Europe. The ecological modelling of amphibians and reptiles relies also on GIS to calculate and process potential distribution models (Guisan and Hofer, 2003; Segurado and Araújo, 2004; Anadon et al., 2006; Arntzen, 2006) and habitat suitability models (Raxworthy et al., 2003; Kearney and Porter, 2004; Dayton and Fitzgerald, 2006; Kaliontzopoulou et al., 2008), as well as in the analysis and forecast of species richness distribution (Soares and Brito, 2007; Ribeiro et al., 2009), climate change effects on species (Meynecke, 2004; Thomas et al., 2004; Araújo and Pearson, 2005; Parra-Olea et al., 2005; Araújo et al., 2006; Araújo et al., 2008) and expansion process of autochthonous species (Sillero, 2009, 2010) or invasive species (Ficetola et al., 2007, 2009; Real et al., 2008). In conservation and management of reptiles, GIS is used in nature reserve design (Ferrier et al., 2002), conservation studies (Root et al., 2003; Santos et al., 2006, 2009; Carretero et al., 2008), forecasting the impacts of road networks (Benayas et al., 2006) and amphibian road-kills (Clevenger et al., 2003; Glista et al., 2007; Sillero, 2008). GIS is widely used in herpetological biogeography, namely in descriptive biogeographical analysis and identification of biogeographical areas (Teixeira et al., 2001, 2002; Wiens et al., 2006; Sillero et al., 2009), phylogeography analysis (Arntzen and Alexandrino, 2004; Real et al., 2005), detection of sympatry areas and hybridization processes (Brito and Crespo, 2002; Costa et al., 2008; Martínez-Freiria et al., 2008), and speciation mechanisms (Kozak and Wiens, 2007). Inside a GIS framework is possible to analyse species dispersion processes through permeability matrix (Ray et al., 2002), detect migration paths (Joly et al., 2003), identify animal movements (Brito, 2003) and assess home range areas (Osterwalder et al., 2004; Knapp and Owens, 2005; Kerr and Bull, 2006; Waldron

et al., 2006; Greenberg and McClintock, 2008; Imansyah et al., 2008). GIS has also been applied to taxonomical studies in order to identify different taxa by modelling their ecological niches (Sá-Sousa, 2000; Brito et al., 2008).

These works confirm the increasing demand of spatial explicit analysis and the expansion of GIS in ecology during the last decade. Although ecology is a marginal field in need of geospatial tools, it is not surprising that geo-information technology is also being developed within the Free/Open Source Software (FOSS) community. The concept of "Free Software" was first defined by Richard M. Stallman in the form of the so-called four freedoms (Mitasova and Neteler, 2004; Tufto and Cavallini, 2005): 1) the freedom to run a program, for any purpose; 2) the freedom to study how the program works, and adapt it to your needs; 3) the freedom to redistribute copies; and 4) the freedom to improve the program, and release your improvements to the public. Points 2 and 4 need obligatorily the access to the program source code. Stallman conceived the GNU-Project in 1983 to support the Free Software concept, and a year later he created the Free Software Foundation. Here, the term free refers not only to the price of acquisition of the software but to a complex of freedoms that allows the user to copy, analyse the source code and even to modify it. The GNU General Public License (GPL) is a software licensing form developed by the Free Software Foundation that grants and protects the four freedoms describes above. Under the GPL, the software code and its modifications must remain "open". GPL is the most widely used license for FOSS nowadays. Over the past few years several FOSS GIS projects have been implemented. Most of them can be found at "FreeGIS Project" web site (www.freegis.org). These projects play an important role in adaptation of GIS technology by stimulating new experimental approaches and by providing access to GIS for a wide spectrum of users. This FOSS philosophy has been extended in some way to data sources availability. Spatial data is in fact essential to perform GIS analysis. Everyday there are more institutions offering their spatial data for free (Kozak et al., 2008).

In this review, we aim to show the feasibility of spatial analysis within FOSS GIS packages, rank these packages using the number of available tools and list several data sources freely available on the Internet. This review is organized in three sections: 1) the review of free sources of geographical data; 2) the comparative analysis of proprietary and free GIS packages and 3) the final remarks.

FREE SPATIAL DATA SOURCES ON INTERNET

Spatial analysis performed by ecologists relate the biology of the species with environmental factors, such as climatic, topographical and habitat data (e.g., Sillero et al., 2009). There are several sources for obtaining these variables, namely topographical, thematic maps and satellite imagery. In some cases, it may be necessary to collect environmental data by fieldwork, which might not be feasible when the costs are high, the study area is very large, or there is no time for data collection (Muldavin et al., 2001). The solution is to acquire data from specialized spatial data providers. These products are usually expensive, worsening in the case of large study areas. This constraint hampers the development of ecological spatial analysis. An alternative solution is to use freely available data, despite a possible decrease of resolution.

There are a large amount of environmental data freely available on Internet. These data are dispersed over several dedicated sites and researchers usually find difficult to retrieve free data from the Internet. An authoritative source of free GIS data is the OSGEO Public Geospatial Data Project (www.osgeo.org/geodata), as well as its GeoNetwork OpenSource metadata harvesting tool (www.geonetwork-opensource.org). These sites are a valid starting point to search for freely available, authoritative data. Kozak et al. (2008) presented a table with links to a few websites, often considered the most important with free environmental data. Available data can be grouped in several different types of spatial information: administrative (country limits, road networks), geographical (country populations), climatic (temperature, precipitation), topographical (altitude, slope), satellite imagery and aerial photography. Spatial data are stored at different resolutions, either spatial (e.g., resolutions of 200 m, 10 km) or temporal (e.g., daily data, annual data). The area covered by the data is also variable: from small areas (municipalities) to the whole world. The Antarctic continent is not included in most spatial data sources (e.g., WorldClim, Shuttle Radar Topography Mission).

We distributed free spatial data sources in five groups: Digital Elevation Models (DEM), Satellite Imagery, Climatic data, Geographical data and Environmental data. We listed websites (Table 1) that we commonly use and searched the internet for others storing these type of data or referencing it (e.g., “FreeGIS Project”: www.freegis.org). Other authors provided several sources (e.g., Kozak et al., 2008) that we also add. Four of the listed websites should be mentioned here: the Shuttle Radar Topography Mission (SRTM), WorldClim, GLOVIS, and SPOT VEGETATION. These provide the most important data for spatial analysis in herpetology, i.e., altitude and derived data; past, current and future climatic series data; and satellite derived data. In fact, these are the websites most accessed by researchers. These data are enough for performing complex biogeographical studies of amphibians and reptiles (e.g., Sillero et al., 2008, 2009).

The Shuttle Radar Topography Mission (SRTM) site offers altitude data at three different spatial resolutions: global dataset is available at 3 arc second and 30 arc second resolutions (approximately 90 m and 1 km, respectively); the current STRM3 version 2.1 global DEM is at 90 m, whereas the so-called “unfinished” 1 arc second (~ 30 m) covers only the conterminous USA. The SRTM was a project of NASA, the National Geospatial-Intelligence Agency, and the German and Italian Space Agencies, performed in February 2000 during 11 days on board Shuttle Endeavour. It used dual radar antennas to acquire interferometric radar data, processing digital topographic data at 1 arc sec resolution (Farr et al., 2007). Recently, other global DEM has become available: the ASTER DEM, with a spatial resolution of 30 m. The SRTM is in the third version, with most errors corrected. ASTER DEM is still in its first version. Both DEM are currently the most complete near-global high-resolution database of Earth’s topography.

WorldClim (Hijmans et al., 2005) offers current series of climatic data: precipitation, mean temperature, maximum temperature and minimum temperature, together with a set of 19 climatic derived variables. There are several spatial resolutions available: 30 arc seconds, 2.5, 5 and 10 arc minutes. Also, climatic variables are available for several future scenarios (e.g., a2a and b2a HadCM3) and years (2020, 2050 and 2080), and for two past periods, the Last Interglacial Period and the Last Glacial Maximum.

The Global Visualization Viewer (GLOVIS) offers satellite imagery from all the Landsat series (1, 3, 4 and 5 MSS; 4 and 5 TM; and 7 ETM+). These Landsat series cover a

Table 1. Data sources freely available on the Internet. The websites have been organized in four groups: Digital Elevation Models, Satellite Imagery, Climatic data, Geographical data, and Environmental data.

Name	Description	Link	Owner
<i>Digital Elevation Models</i>			
GTOPO30	USGS DEM 30 seg	http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html	USGS
Global Land One-km Base Elevation Project	National Oceanographic Data Center DEM	http://www.ngdc.noaa.gov/mgg/topo/globe.html	NOAA
SRTM	Shuttle Radar Topography Mission	http://srtm.csi.cgiar.org/	NASA
Satellite Geodesy	SRTM30_PLUS Bathymetry	http://topex.ucsd.edu/WWW_html/srtm30_plus.html	University of California San Diego
Global ASTER DEM	ASTER Global Digital Elevation Model 30m	www.gdem.aster.ersdac.or.jp	NASA/METI
HYDRO1k	HYDRO1k Elevation Derivative Database	http://edc.usgs.gov/products/elevation/gtopo30/hydro/	USGS
<i>Satellite Imagery</i>			
free VEGETATION distribution site	SPOT Vegetation sensor-free products	http://free.vgt.vito.be/	SPOT
GLCF	Global Land Cover Facility	http://glcf.umiacs.umd.edu/index.shtml	NOAA
Global Land 1-KM AVHRR Project	Advanced Very High Resolution Radiometer data	http://edc2.usgs.gov/1KM/	NOAA
geoNetwork	Find Interactive Maps, GIS datasets, Satellite Imagery and Related Applications	http://www.fao.org/geonetwork/srv/en/main.home	FAO
SEAMLESS	Seamless Data Distribution System, Earth Resources Observation and Science	http://seamless.usgs.gov/website/Seamless/	USGS
Landsat.org	Landsat programme home page	http://www.landsat.org/	NASA
LAADS	Level 1 and Atmosphere Archive and Distribution System	http://ladsweb.nascom.nasa.gov/	NASA

(Continued)

Table 1. (continued).

Name	Description	Link	Owner
LP DAAC	ASTER and MODIS Land Data Products and Services	https://lpdaac.usgs.gov/	USGS
WIST	Warehouse Inventory Search Tool	https://wist.echo.nasa.gov/	NASA
Global Visualization Viewer	Satellite imagery	http://glovis.usgs.gov/	USGS
EarthExplorer	Satellite imagery	http://edcns17.cr.usgs.gov/EarthExplorer/	USGS
<i>Climatic Data</i>			
WORLDCLIM	Climatic data from Hijisman et al 2005	http://www.worldclim.org/	Hijisman et al
BIOCLIM	Bioclimatic parameters for modelling software Bioclim	http://cres.anu.edu.au/outputs/anuclim/doc/bioclim/html	Australian National University
Global-PET and Global-Aridity datasets	Global Potential Evapo-Transpiration and Aridity Index	http://csi.cgiar.org/aridity/index.asp	CGIAR-Consortium for Spatial Information
GCM Data Portal	Future climatic scenarios	http://gisweb.ciat.cgiar.org/GCMPPage/	IPCC
<i>Geographic data</i>			
Atlas of the Biosphere	Human impacts, land use, ecosystems, water resources	http://www.sage.wisc.edu/atlas/	SAGE
Digital Chart of the World	Administrative data	http://www.maproom.psu.edu/dcw/	Penn State University
Geo Data Portal	Environmental and geographical data about World	http://geodata.grid.unep.ch/	United Nations Environment Programme
gData	Free geographic (GIS) data for any country in the world	http://biogeo.berkeley.edu/bgmgdata.php	Berkeley University
geoNetwork	Find Interactive Maps, GIS datasets, Satellite Imagery and Related Applications	http://www.fao.org/geonetwork/srv/en/main.home	FAO
Country Files (GNS)	Complete Files of Geographic Names for Geopolitical Areas	http://earth-info.nga.mil/gns/html/cntry_files.html	GNS

(Continued)

Table 1. (continued).

Name	Description	Link	Owner
GIS DataFinder	Administrative data	http://www.lib.unc.edu/reference/gis/datafinder/index.html	Davis Library Reference Department
EarthTrends	Links to resources	http://earthtrends.wri.org/index.php	World Resources Institute
<i>Environmental data</i>			
Geo Data Portal	Environmental and geographical data about World	http://geodata.grid.unep.ch/	United Nations Environment Programme
European Environment Agency	Environmental data about Europe	http://www.eea.europa.eu/	European Union
European Distributed Institute of Taxonomy	Global and European GIS layers	http://edit.csic.es/GISdownloads.html	European Union
GIAM	Global Map of Irrigated Area	http://www.iwmgiam.org/info/main/index.asp	IWMI Netherlands
HYDE	History Database of the Global Environment	http://www.mnp.nl/en/themasites/hyde/index.html	Environmental Assessment Agency
NODC NOAA	National Oceanographic Data Center	http://www.nodc.noaa.gov/	NOAA

large temporal interval: 1 and 3 MSS, 1973-1976; 4 and 5 MSS, 1984-1987; 4 and 5 TM, 1984-2003; 7 ETM+, 1999-2003. The Landsat 5 TM and 7 ETM+ are currently operative, but with some important problems hampering to record images in a correct way.

The VEGETATION site offers global data on 10 days-temporal series of Normalized Difference Vegetation Index (NDVI), with a spatial resolution of 1 km. VEGETATION is a sensor of SPOT satellite, recording daily NDVI data.

There are other sites providing data from satellite sensors. For instance, the largest temporal series of NDVI (from 1989 to present) comes from the Advanced Very High Resolution Radiometer (AVHRR), located at EarthExplorer website (together with other satellite data). MODIS also offers data on vegetation indexes, surface temperature and land cover. The Global Land Cover Facility focus on research using satellite data to assess land cover change for local to global systems.

PROPRIETARY AND FREE/OPERN SOURCE GIS SOFTWARES

Currently, proprietary packages (e.g., ArcGIS 9.3 by ESRI www.esri.com and Idrisi version Taiga by Clark Labs www.clarklabs.org) seem to be the first choice for herpetologists (and biologists, in general). In fact, ArcGIS family products is one of the most used GIS softwares. ArcGIS is an integrated collection of GIS software products for building and deploying a complete GIS (i.e., with vector and raster functions). The variety of ArcGIS applications can run on a great range of hardware, from simple desktops to servers and handhelds, providing GIS tools wherever needed. In the last years, many government agencies have adopted ESRI's standard vectorial format (shapefile) as the common format for their geographical products. There is also an open source format: the Geography Markup Language (GML), a grammar defined by the Open Geospatial Consortium (OGC) to express geographical features, including not only conventional vector data, but also coverages and raster data.

Nowadays there is a large availability of free GIS softwares, most of them open source and released under the terms of the GPL, running on a variety of platforms (Windows, Linux, Mac OS). One of the oldest GIS software is GRASS (Geographic Resources Analysis Support System: grass.osgeo.org; current version is 6.4.0 RC5) originally developed by the US Army Construction Engineering Research Laboratories as a tool for land management and environmental planning, and currently maintained as FOSS. GRASS is oriented for raster analysis, including tools for spatial modelling, visualization, management and processing of satellite imagery. The analysis of vectorial data improved in the newer versions. GRASS has been under continuous development since 1982, involving a large number of federal US agencies, universities, and private companies.

Other FOSS is Quantum GIS (QGIS: www.qgis.org; version 1.4.0 Enceladus), which supports vector and raster formats. QGIS includes some spatial analysis tools for vectorial data and a GRASS plug-in, allowing the use of a full GRASS installation within QGIS. This software can easily connect to a PostGIS/PostgreSQL database server to retrieve geographical information. OpenModeller (openmodeller.sourceforge.net) is a QGIS based project specifically oriented at species distribution modelling. In fact, it is a heavily modified QGIS, with several modelling tools added using the native QGIS plugin mechanism.

gvSIG (www.gvsig.gva.es; version 1.9) is also a vectorial GIS capable of using most common vector and raster formats. GRASS, QGIS and ILWIS are also able to read (and partially write) almost all known GIS vector and raster formats, since they rely on Frank Warmerdam GDAL/OGR interoperability library, which gvSIG uses in part. SEXTANTE (www.sextantegis.com; version 0.55) provides gvSIG with both raster and vector geographical analysis capabilities with over 150 extensions for geo-statistics and hydrological analysis, creation of vegetation indexes and profiles. It is also provided a lighter version of gvSIG for mobile devices. Both QGIS and gvSIG work in several operating systems. GRASS, QGIS and gvSIG can read geographical data from remote sources through WMS¹, WCS² or WFS³ standard protocols.

The Integrated Land and Water Information System (ILWIS; www.itc.nl/ilwis/default.asp; version 3.6) is a Windows-based raster GIS and Remote Sensing software, developed commercially by the ITC (Faculty for Geo-Information Science and Earth Observation of the University of Twente, The Netherlands) up to its last release (version 3.4) and since 2007 is maintained as FOSS. ILWIS comprises a complete package of image processing, spatial analysis and digital mapping.

DIVA-GIS (version 7.1.7) is focused on vector analysis and developed particularly for mapping and analysing biodiversity data. It provides tools to predict species distributions using the BIOCLIM or DOMAIN models.

There are other softwares mainly for visualizing vector and raster format such as Kosmo by SAIG (Sistemas Abiertos de Información Geográfica; www.saig.es), Gaia (www.thecarbonproject.com/gaia.php), OpenJump (www.openjump.org) and ArcReader (www.esri.com).

We listed in the Appendix 1 the most commonly used functions in GIS and their availability in the six software compared in this study (ArcGIS 9.3, gvSIG 1.9, ILWIS 3.6, Quantum GIS 1.4.0, GRASS 6.4.0 RC5, and DIVA-GIS 7.1.7). These functions are explained in Appendix 2 and have been separated in three groups: vector (with 59 functions), raster (with 58) and typographic and layout production (with 12). As explained above, most of GIS programs are initially designed to work exclusively in either the vector or raster domain, with some capability to operate in the other. Therefore, a particular software could have a high number of functions for a specific format, but none or a few in the other. For example, the former versions of gvSIG had several vector functions and few raster functions. Our intention is to rank the six GIS software by the number of available functions in each groups. The highest ranked software will be the software with more functions available.

ArcGIS 9.3 occupies the first position (Table 2), thus it is the software that presents most of the tools considered here. ArcGIS has a modular structure, i.e., the functions are included in several modules. To use all the functions, the user need to buy all modules. For example, raster functions are included in the module Spatial Analyst and without this module, ArcGIS is mainly a vector-oriented GIS: it can read raster files just as images and

¹ The Open Geospatial Consortium (OGC) defines a Web Map Service (WMS) as a standard protocol for serving georeferenced map images over the Internet that are generated by a map server using data from a GIS database.

² The OpenGIS® Web Coverage Service Interface Standard (WCS) is a standard interface and operations that enables interoperable access to geospatial coverages, as defined by the OGC.

³ The Open Geospatial Consortium Web Feature Service Interface Standard (WFS) provides an interface allowing requests for geographical features across the web, using platform-independent calls, as defined by the OGC.

Table 2. Global results of available functions on GIS softwares. See in Appendix 1, Table 3 for vector functions, Table 4 for raster functions and Table 5 for layout functions. See Appendix 2 for function definitions. Software versions: ArcGIS 9.3; gvSIG 1.9; ILWIS 3.6; QGIS 1.4.0; GRASS 6.4.0 RC5; DIVA 7.1.7.

	ArcGIS	gvSIG	ILWIS	QGIS	GRASS	DIVA
Vector	56	50	28	50	38	15
Raster	46	46	38	37	40	23
Layout	12	10	9	7	60	6
Total	114	106	75	94	84	44

not as true rasters, without any processing capability except for colour palette adjustments and false-colour band assignment, and even the geoprocessing of vectorial data is limited in the most basic license with native tools. However, this modular scheme is a advantage for proprietary software: the user can buy only the packages that cover his needs and does not have to buy other specific tools. Nevertheless, ArcGIS is capable of use external tools written in several programming languages (i.e., Visual Basic for Applications, Python) enhancing its range of application. A high number of these scripts are free and available at ESRI's website (<http://arcscrips.esri.com>). Therefore, some functions not available in ArcGIS out of the box can be performed through an external script.

gvSIG 1.9 ranks second, with 106 functions in total. It has also a modular structure, with freely available modules. One of the major advantages is the ability of reading directly several formats (without importing them previously), both vector and raster, and process them. It has good graphical production capabilities. Despite being mainly focused on territory management, gvSIG has enough functions for ecological analysis.

QGIS 1.4.0 is a good software for visualizing data and is capable of reading a large number of file formats. It has many functions for spatial analysis with the GRASS plug-in, although it only works directly with GRASS formats (without importing data previously through GDAL/OGR library). It has good graphical production capabilities, including tools to build scales, legends and it works with several maps. This last version includes many vectorial tools, for analysis, management, research and geoprocessing. It also has a tool to import scripts to add new functions from several repositories. These features, and especially the user-friendly interface, extends the potential use of this software.

GRASS 6.4.0 RC5 and ILWIS 3.6 have many functions, particularly oriented towards rasters and imagery processing. GRASS and ILWIS can read many formats through the GDAL/OGR library. However, GRASS has a well defined project that often results in duplication of data. While the GRASS project may present several advantages for advanced users, the inexperienced user will find difficult to apprehend the GRASS paradigm. For users with large databases of spatial data on other formats, this limitation can hamper the use of these FOSS GIS. GRASS works with projects that have a previously user defined extent (before entering data) and where external files should be imported. The GRASS Location/Mapset paradigm avoids tampering with projections and datums, and it is the only physical representation explicitly designed to allow true concurrent, multi-user access. A common mistake in ESRI products is not to define the raster analysis environment; the user can mix rasters with different cell sizes and awkward coordinate

reference systems, which could cause severe errors not only in map algebra but also in geostatistical applications. GRASS data structures instead completely eliminate the problem. On the other hand, ILWIS is not capable of working with very large files. Overall, these packages are very useful for ecological analysis.

DIVA-GIS 7.1.7 is a software oriented specifically to biogeography and diversity studies. Despite a small number of functions (15 vector, 23 raster and six layout functions), those are extremely useful in biogeography studies. Furthermore, some functions are exclusive to DIVA-GIS (e.g. similarity indexes), constituting a good complement to other software.

Briefly, gvSIG is the FOSS with more functions (106) followed by QGIS with 94 and GRASS with 84. ILWIS has 75 functions. We can consider gvSIG the most complete FOSS specially for its capacity of working directly with several data formats out of the box, both vector and raster files. QGIS has more functions than GRASS thanks to the new vector tool plug-in included in the last version (1.4.0 Enceladus).

FINAL REMARKS

Events like the elimination of Selective Availability in GPS devices in 2000 with the increase of signal quality and precision, the increased performance of altitude data with the Shuttle Radar Topography Mission in 2000, and the public availability of all archives of Landsat satellites in 2009 were very important to support the FOSS philosophy, firstly proposed by Richard M. Stallman, as explained above. Science is the most important motor providing progress to the humanity. To achieve this objective, gathered data should be made available publicly and freely.

In the scope of this review, we should emphasize some of the advantages of working with Free/Open Source Software (FOSS): most of the packages presented here interact with each other and with other FOSS (e.g., server databases, statistical packages) and communicate with open formats, common to a huge range of software (e.g., graphical production software). This constitutes a vast collection of functions that cover virtually all potential applications to ecology. Moreover, most of the FOSS is being continuously updated and upgraded with new functionalities. This increases the difficulty of ranking GIS software, due to the fact that the evaluation of the presence of a particular feature is not straightforward: some software do not present an easy access to a feature, and it does not mean the feature is not present through a command line, for instance. Therefore, the rank presented in this review reflects the user-friendliness of the GIS packages.

This review does not cover functionalities neither software for more advanced users. One example of a function of this type is the use of a command line for batch processing. This function is common between ArcGIS, gvSIG, GRASS and ILWIS, for instance, and is extremely useful for processing/production of large datasets. The use of the command line and scripts can overcome the apparent limitations of a software. For a paradigmatic example, the R statistical computing environment (R Development Core Team, 2009) is a free programming language widely used in science and has modules for spatial and geostatistical analysis. One great advantage of this language is the advanced control of the processing, wide range of available modules and, as an example, the interaction with GRASS.

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APPENDIX 1

Table 3. List of vectorial functions, grouped by similar characteristics. Six softwares were analysed: one proprietary (ArcGIS 9.3); and five FOSS (gvSIG 1.9, ILWIS 3.6, Quantum GIS 1.4.0, GRASS 6.4.0 RC5 and DIVA-GIS 7.1.7). We counted the number of functions available per software. The most complete software will be the software with more available functions. See in this Appendix, Table 4 for raster functions and Table 5 for layout functions. See Table 2 on manuscript for global results. See Appendix 2 for function definitions.

Vector	ArcGIS	gvSIG	ILWIS	QGIS	GRASS	DIVA
<i>Basic Operations</i>						
Shapefile reading	YES	YES		YES		YES
Import/Export Shapefiles	YES	YES	YES	YES	YES	YES
Vector to Raster	YES	YES	YES	YES	YES	YES
Vector projection	YES	YES	YES	YES	YES	YES
Attributes reading	YES	YES	YES	YES	YES	YES
Modeller	YES	YES	YES			
TOTAL	6	6	5	5	4	5
<i>Map Digitalization</i>						
Vector digitalization	YES	YES	YES	YES	YES	
Vector edition	YES	YES	YES	YES	YES	
Image georeferencing	YES	YES	YES	YES	YES	YES
TOTAL	3	3	3	3	3	1
<i>Selection</i>						
Selection by attributes	YES	YES	YES	YES	YES	YES
Selection by location	YES	YES		YES	YES	
TOTAL	2	2	1	2	2	1

(Continued)

Vector	ArcGIS	gvSIG	ILWIS	QGIS	GRASS	DIVA
<i>Tables Operations</i>						
Table edition	YES	YES	YES	YES	YES	
Table Calculator	YES	YES	YES	YES	YES	
Table statistics	YES	YES	YES	YES	YES	YES
Table join	YES	YES	YES	YES	YES	
Table link	YES	YES	YES			
Summarize Tables	YES					
Graphs	YES	YES	YES			
TOTAL	7	6	6	4	4	1
<i>Point Operations</i>						
Points to lines	YES					
Points to polygons	YES					YES
Add data points	YES	YES	YES	YES	YES	YES
Calculate coordinates	YES			YES		YES
Vectorial buffers	YES	YES		YES	YES	
Merge	YES	YES	YES	YES	YES	
Dissolve	YES	YES		YES	YES	
Clip	YES	YES	YES	YES		
Break features	YES	YES		YES		
Convex Hull	YES	YES		YES	YES	YES
Voronoi tessellation	YES	YES		YES	YES	
Delaunay tessellation	YES	YES		YES	YES	
Select at random	YES			YES	YES	
Autocorrelation	YES	YES	YES			YES
TOTAL	14	10	4	11	8	5
<i>Polylines Operations</i>						
Lines to polygons	YES	YES	YES	YES	YES	
Lines to points	YES	YES	YES	YES	YES	
Vectorial buffers	YES	YES		YES	YES	
Merge	YES	YES	YES	YES	YES	
Dissolve	YES	YES		YES	YES	
Clip	YES	YES	YES	YES		
Vectorial grids				YES		
Break features	YES	YES		YES	YES	
Generalization	YES	YES		YES	YES	
TOTAL	8	8	4	9	7	0
<i>Polygon Operations</i>						
Polygons to points	YES		YES			
Polygons to lines	YES	YES	YES	YES	YES	

(Continued)

Vector	ArcGIS	gvSIG	ILWIS	QGIS	GRASS	DIVA
Intersection	YES	YES		YES	YES	
Union	YES	YES		YES	YES	
Difference	YES	YES		YES	YES	
Vectorial buffers	YES	YES		YES	YES	
Merge	YES	YES		YES	YES	
Dissolve	YES	YES		YES	YES	
Clip	YES	YES	YES	YES		
Spatial join	YES	YES		YES		YES
Vectorial grids			YES	YES	YES	
Centroids calculation	YES	YES		YES	YES	
Count points in polygons		YES		YES		
Calculate area	YES			YES		
Break features	YES	YES		YES		
TOTAL	13	12	4	14	9	1
<i>Network Analysis</i>						
Euclidean Distance	YES	YES		YES		YES
Cost Distance	YES	YES				
Nearest Neighbour	YES	YES	YES	YES	YES	
TOTAL	3	3	1	2	1	1
TOTAL	56	50	28	50	38	15

Table 4. List of raster functions, grouped by similar characteristics. See Table 3 for more information. See in this Appendix, Table 3 for vector functions and Table 5 for layout functions. See Table 2 on manuscript for global results. See Appendix 2 for function definitions. Software versions: ArcGIS 9.3; gvSIG 1.9; ILWIS 3.6; QGIS 1.4.0; GRASS 6.4.0 RC5; DIVA 7.1.7.

Raster	ArcGIS	gvSIG	ILWIS	QGIS	GRASS	DIVA
<i>Basic Operations</i>						
Import/Export Ascii	YES	YES	YES	YES	YES	YES
Import/Export raw data	YES	YES	YES	YES	YES	YES
Raster to Vector	YES	YES	YES	YES	YES	
Raster projection	YES	YES		YES	YES	
Pixel information	YES	YES	YES	YES	YES	YES
Raster Stacks	YES		YES			YES
Fusion bands		YES		YES	YES	
Histogram	YES	YES	YES			YES
Colour table	YES	YES	YES	YES	YES	
Radiometric Enhanced	YES	YES	YES			
TOTAL	9	9	8	7	7	5

(Continued)

Raster	ArcGIS	gvSIG	ILWIS	QGIS	GRASS	DIVA
<i>Spatial Basic Analysis</i>						
Raster Algebra	YES	YES	YES	YES	YES	YES
Buffer rasters	YES	YES		YES	YES	
Raster Descriptive Statistics	YES	YES	YES	YES	YES	YES
Random value rasters	YES	YES		YES	YES	
Clip rasters	YES	YES	YES			YES
Raster Spatial Join	YES					YES
Values Composites	YES		YES			YES
Neighbourhood statistics	YES	YES		YES	YES	YES
Zonal statistics	YES	YES				
Aggregate	YES	YES	YES	YES	YES	YES
Resample	YES		YES	YES	YES	
Mosaic	YES	YES	YES	YES	YES	
TOTAL	12	9	7	8	8	7
<i>Raster Statistics</i>						
Raster Correlation	YES	YES	YES	YES	YES	YES
Raster Regression	YES	YES		YES	YES	YES
Raster Multiple Regression	YES	YES				YES
Raster PCA	YES	YES	YES		YES	
Raster Factor analysis			YES		YES	
Cluster analysis		YES	YES			YES
Fit distribution analysis		YES				
TOTAL	4	6	4	2	4	4
<i>Raster Comparisons</i>						
Cross-tabulation			YES	YES	YES	YES
Kappa			YES	YES	YES	YES
Similarity analysis						YES
ROC analysis		YES				YES
TOTAL	0	1	2	2	2	4
<i>Image Analysis</i>						
Reclassification	YES	YES	YES	YES	YES	YES
Masks	YES	YES	YES	YES	YES	
Filters	YES	YES	YES	YES	YES	
Raster Classification	YES	YES	YES		YES	
Accuracy Assessment						
Vegetation Indexes		YES	YES			
Image transformations		YES		YES	YES	
Density Slicing			YES			
TOTAL	4	6	6	4	5	1

(Continued)

Raster	ArcGIS	gvSIG	ILWIS	QGIS	GRASS	DIVA
<i>Interpolation</i>						
Semivariogram	YES	YES	YES			
IDW	YES	YES	YES	YES	YES	
Spline	YES			YES	YES	
Kriging	YES	YES	YES			
Trend Surface	YES	YES	YES	YES	YES	
TIN	YES	YES		YES		
TOTAL	6	5	4	4	3	0
<i>Digital Elevation Models</i>						
Slope	YES	YES	YES	YES	YES	YES
Aspect	YES	YES		YES	YES	YES
Hillshading	YES	YES		YES	YES	
Visibility analysis	YES	YES		YES	YES	
Contour analysis	YES	YES		YES	YES	
3-D Visualization	YES		YES	YES	YES	
TOTAL	6	5	2	6	6	2
<i>Hydrology</i>						
Flow Analysis	YES	YES	YES	YES	YES	
Direction analysis	YES	YES	YES	YES	YES	
Watershed analysis	YES	YES	YES	YES	YES	
Fill analysis	YES	YES	YES	YES	YES	
Stream calculation	YES	YES	YES		YES	
TOTAL	5	5	5	4	5	0
TOTAL	46	46	38	37	40	23

Table 5. List of layout functions, grouped by similar characteristics. See Table 3 for more information. See in this Appendix, Table 3 for vector functions and Table 4 for raster functions. See Table 2 on manuscript for global results. See Appendix 2 for function definitions. Software versions: ArcGIS 9.3; gvSIG 1.9; ILWIS 3.6; QGIS 1.4.0; GRASS 6.4.0 RC5; DIVA 7.1.7.

Layout	ArcGIS	gvSIG	ILWIS	QGIS	GRASS	DIVA
<i>Basic Operations</i>						
Export a map	YES	YES	YES	YES	YES	YES
Palette colours	YES	YES	YES	YES	YES	YES
Scale	YES	YES	YES	YES	YES	YES
North Arrow	YES	YES	YES	YES	YES	YES
Legend	YES	YES	YES	YES		YES
Text	YES	YES	YES	YES	YES	YES

(Continued)

Layout	ArcGIS	gvSIG	ILWIS	QGIS	GRASS	DIVA
Figure	YES	YES	YES	YES		
TOTAL	7	7	7	7	5	6
<i>Advanced Operations</i>						
Insert several maps	YES	YES	YES			
Advanced text	YES	YES				
Freehand text	YES					
Insert grid	YES	YES				
Insert geogrid	YES		YES		YES	
TOTAL	5	3	2	0	1	0
TOTAL	12	10	9	7	6	6

APPENDIX 2

Vector functions

Shapefile reading: reads directly files in shapefile format, without importing them previously.

Import/Export Shapefiles: imports and/or exports shapefiles.

Vector to Raster: transforms vector files to raster files.

Vector projection: transforms a vector file from its original projection to another one.

Attributes reading: reads the attributes stored in a table.

Modeller: functions can be concatenated and stored for future uses.

Vector digitalization: transforms data on a physical map or an image to a vector file.

Vector edition: modifies the topology of a vector file.

Image geo-referencing: correctly places an image inside a given coordinate reference system.

Selection by attributes: selects entities and attributes using boolean operators on an attribute table.

Selection by location: selects entities and attributes using topological criteria.

Table edition: modifies table values.

Table Calculator: performs mathematical calculations among table fields.

Table statistics: descriptive statistics of table fields.

Table join: joins two tables through a common field.

Table link: the values of a table are read in a second table.

Summarize Tables: applies an aggregation function such as sum, mean, count, to a field by grouping its values based on unique values from another field.

Graphs: table attributes can be represented in a graph.

Points to lines, Points to polygons; Lines to points, Lines to polygons; etc: transforms a specific type of vector file to another type.

Add data points: imports a list of coordinates to a point vector file.

Calculate coordinates: adds coordinates to the attribute table of a point vector file.

Vectorial buffers: calculates polygons of constant distance around points, lines or polygons.

Merge: joins several vector files of the same type (point, line or polygon).

Dissolve: joins item of a vector file by the same attribute.

Clip: extracts a part of a vector file with a polygon.

Break features: exports each item of a point, line or polygon vector file to a different and independent file.

Convex Hull: calculates the minimum convex polygon enclosing a group of points.
Voronoi/Delaunay: two particular types of vectorial interpolations.
Select at random: selects a sample of points from a file.
Autocorrelation: calculates the correlation among the points of the same file.
Vectorial grids: builds rectangular polyline or polygon cartographical grids at constant distances.
Generalization: reduces nodes in a line or polygon vector, preserving its attributes but yielding a coarser geometry. Intervals are generally not regular, since generalisation algorithms must leave as much nodes as possible to preserve the original curvature of an entity.
Intersection: joins the spatially common parts of two vector files in only one file.
Union: joins two vector files in only one file, either spatially common or non-common parts.
Difference: joins the not common parts of two vector files in only one file.
Spatial join: transfers attributes between two vectors (of any type) based on coincident locations.
Centroids calculation: calculates the central point of a polygon.
Count points in polygons: counts the number of points inside the limits of a polygon.
Calculate area: adds the perimeter/area values to the items of a polygon table file.
Euclidean Distance: calculates the Euclidean distance between two points.
Cost distance: calculates the cost of going from a place to another place along a specific path depending on the value of an attribute.

Raster functions

Import/Export Ascii: imports/exports raster files in ASCII format.
Import/Export raw data: imports/exports raster files to other formats.
Raster to Vector: transforms raster files to vector files.
Raster projection: transforms a raster file from its original projection to another one.
Pixel information: reads pixel values.
Raster Stacks: includes several raster files or bands inside an unique file.
Raster Algebra: performs mathematical operations among rasters.
Raster buffers: calculates a buffer of constant distance.
Raster Descriptive Statistics: descriptive statistics of pixel values.
Random value rasters: creates a raster with random values.
Clip rasters: extracts a part of a vector file with a polygon or another raster.
Raster Spatial Join: transfers the attributes of a raster file to a point file.
Values Composites: calculates a new raster file from a list of raster using a mathematical function.
Neighbourhood statistics: quantifies and visualizes spatial variation in pixel.
Zonal statistics: calculates statistics on values of a raster within the zones of another dataset.
Aggregate: increases the size of pixels (and reduces the spatial resolution) using a mathematical operator.
Resample: changes the pixel size in the image.
Raster Correlation: calculates the correlation among a group of rasters.
Raster Regression: calculates a regression between two rasters.
Raster Multiple Regression: calculates a multiple regression between several rasters.
Raster PCA: calculates a Principal Component Analysis between two rasters.
Raster Factor analysis: calculates a factorial analysis between two rasters.
Cluster analysis: calculates a cluster analysis between two rasters.
Fit distribution analysis: fits the values of a rasters to a specific distribution curve.
Data sampling: extracts randomly pixel values.
Autocorrelation: measures the spatial autocorrelation inside a raster.
Cross-tabulation: compares a group of raster by their common values (normally for categorical data).

Kappa: a statistical measure of similarity between two raster.

Similarity analysis: index for measuring the similarity among values of two raster.

Reclassification: modifies pixel values using rules.

Masks: classifies a part of a raster as background.

Filters: modifies pixel values using mathematical operators in a square with a specific size.

Raster Classification: statistical method for splitting a image in significant groups.

Accuracy Assessment: method for validating a raster classification.

Vegetation Indexes: indexes for detecting vegetation in satellite imagery.

Image transformations: transformations of satellite imagery, namely for classification purposes.

Density Slicing: classifies a image by groups with the same number of pixels.

Semivariogram: function expressing the influence of the value of a spatial variable measured in a given point on its neighbours at increasing distances and at different directions.

IDW, Spline, etc: different interpolation methods.

Slope: calculates the slope inside each pixel of a DEM.

Aspect: calculates the cardinal orientation inside each pixel of a DEM.

Hillshading: calculates a shade model from a DEM.

Visibility analysis: calculates visible areas from a point.

Contour analysis: extracts lines connecting points at equal values (isopleths) from continuous raster data such as elevation or rainfall.

3-D Visualization: visualizes a raster in a 3-D environment.

Flow Analysis: calculates the amount of water flow through each pixel of a DEM.

Direction analysis: calculates the direction of water through each pixel of a DEM.

Watershed analysis: calculates the watersheds in a DEM.

Fill analysis: eliminates depressions in a DEM.

Stream calculation: calculates stream lines in a DEM.

Layout functions

Export a map: produces a map which is exported in a particular image format or in pdf format.

Palette colours: the features inside the map can be represented with different colours and classify methods.

Scale: inserts a graphical scale in the map.

North Arrow: inserts a north arrow in the map.

Legend: inserts the legend of the features represented in the map.

Text: inserts text in the map.

Figure: inserts figures in the map.

Insert several maps: inserts several maps in the same sheet.

Advanced text: the text can be rotated.

Freehand text: the text can be placed over a curved segment.

Insert grid: inserts a non geo-referenced grid.

Insert geogrid: inserts a geo-referenced grid.