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GRASS GIS: A multi-purpose open source GIS

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ABSTRACT

The GIS software sector has developed rapidly over the last ten years. Open Source GIS applications are gaining relevant market shares in academia, business, and public administration. In this paper, we illustrate the history and features of a key Open Source GIS, the Geographical Resources Analysis Support System (GRASS). GRASS has been under development for more than 28 years, has strong ties into academia, and its review mechanisms led to the integration of well tested and documented algorithms into a joint GIS suite which has been used regularly for environmental modelling. The development is community-based with developers distributed globally. Through the use of an online source code repository, mailing lists and a Wiki, users and developers communicate in order to review existing code and develop new methods. In this paper, we provide a functionality overview of the more than 400 modules available in the latest stable GRASS software release. This new release runs natively on common operating systems (MS-Windows, GNU/Linux, Mac OSX), giving basic and advanced functionality to casual and expert users. In the second part, we review selected publications with a focus on environmental modelling to illustrate the wealth of use cases for this open and free GIS.

Software availability

- GRASS GIS software:
  - Free under the GNU GPL license and can be obtained from http://grass.osgeo.org/
- Operating System requirements:
  - MS-Windows XP or newer, MacOS X 10.4.10 or newer, recent GNU/Linux or a UNIX variant

1. Introduction

The capabilities of Geographic Information Systems (GIS) to integrate heterogeneous digital data into joint databases and to provide basic and advanced data analysis and visualization techniques led to the widespread use of GIS in public administration, industry and research. GIS has evolved to be used in a multitude of disciplines (Star and Estes, 1991; Foody, 2008) and has been deployed on systems ranging from grid computing to embedded systems in smartphones. Since the early days of GIS the market has evolved into the multi-billion dollar range (Goodchild and Haining, 2004). Two principal development paradigms are being followed: the open source and the closed source (often proprietary) development models. In the case of Free and Open Source Software, the source code is typically published under a Free Software license with end-user rights to run the program for any purpose, to study how the program works, to adapt it, and to redistribute copies including modifications.

The idea of Open Source Software may be as old as software development itself since code originating from universities and government laboratories has often been made available first in the public domain. In the 1990s a series of Open Source GIS software projects for both desktop and server systems was established in various GIS sectors, including software libraries for map reprojection and data format conversion, desktop GIS, Web mapping/Web GIS, spatial SQL databases, geostatistics, and metadata catalogues. In the field of environmental modelling, GIS technologies have been adopted in an early stage to capture and analyse spatial relations.

In the desktop GIS sector, the Geographical Resources Analysis Support System (GRASS, http://grass.osgeo.org) is one of the core components of the Open Source geospatial software stack.

GRASS is a multi-purpose Open Source GIS which can be used for geospatial data production, analysis, and mapping (Neteler and

Abbreviations: GRASS, Geographical Resources Analysis Support System; GIS, Geographic Information System; GPL, General Public License; OSGeo, Open Source Geospatial Foundation.

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Mitasova, 2008). It can handle 2D and 3D (voxel) raster data, includes a topological 2D and 3D vector engine with SQL-based attribute management, and vector network analysis functions. The database backend may be chosen from a number of popular alternatives. Furthermore, GRASS offers many spatial modelling algorithms, 3D visualization, as well as image processing routines pertaining to LiDAR and multi-band imagery. GRASS integrates well with other Open Source and proprietary software packages for geostatistical analysis, cartographic output, and Web GIS applications (Neteler et al., 2008). Along with a textbook (Neteler and Mitasova, 2008), a rich data set of free geospatial data has been published as a ready-to-use GRASS database as well as in standard GIS formats.

This paper seeks to provide some background information about the unique history of the GRASS GIS project, to illustrate the current features of the software, and to review selected GRASS applications published in the literature.

2. Background

In the 1980s, GRASS was the earliest Open Source GIS to reach production status and the first to support both raster and vector data models. Development began in 1982 by the United States Army Corps of Engineers (Construction Engineering Research Laboratory, CERL) with software distributed through academic and public administration channels. In the early 1990s, CERL created the Open GRASS Foundation which evolved into the Open GIS Consortium (OGC, today known as the Open Geospatial Consortium). The discontinuation of GRASS development by CERL in 1996 led to the formation of the international GRASS Development Team in its present form.

Originally published as public domain software, the license of GRASS was changed in 1999 to the GNU General Public License (GPL, see http://www.gnu.org), a popular Free Software license (Mitasova and Neteler, 2004). In 2006, the GRASS project became a founding member of the Open Source Geospatial Foundation (OSGeo, http://www.osgeo.org), and, through this, it holds today formal membership in a not-for-profit legal entity. Acceptance to OSGeo depends on a successful project incubation process which includes a detailed source code audit to identify any license incompatibilities in the code. This incubation process also confirms that the project is supported by a healthy community, including validation of the rules and processes governing the project's management. The project's infrastructure was shifted to OSGeo in order to establish a centralized new home for its website, Wiki help system, source code repository, community add-on module repository, and integrated bug tracking system.

Through the use of the GPL, GRASS may be installed and used without restriction in any commercial or non-commercial environment at no cost. Further benefits include the possibility to give the software along with course material legally for free to students in academic environments, e.g. on personalized USB memory sticks or for download. Additionally, and in contrast to most proprietary GIS software packages, GRASS GIS is portable, that is, it can be operated on various computer operating systems (GNU/Linux, Mac OSX, and MS-Windows operating systems are all officially supported). While Open Source Software licensed under the GPL can typically be freely downloaded from the Internet, it can be nonetheless used without restriction in for-profit commercial contexts and sold for profit as long as the terms of the GPL are fulfilled. In-house modifications and extensions can be kept private – the sharing of source code does not apply to data produced with it and applies only when redistributing the software. For example, GRASS can be used to produce value-added products taking advantage of its processing capabilities, or GRASS can be embedded into service chains as the GIS backend for Web Services.

The GPL further ensures that end-users can fully study, audit, modify, and extend the underlying algorithms and methods for this and any future version of GRASS. The GRASS project follows a typical Open Source development paradigm, with the source code being maintained in a public repository by a group of both paid and volunteer developers. Each change is subject to public peer review of code style, functionality, and quality. For end users, this development model provides highly interoperable and quality software at no cost. This approach is both flexible and immune to single vendor lock-in. In a scientific context, the reproducibility of results and quality assessment of methods is greatly facilitated since full access to the underlying algorithms is guaranteed. Substantial parts of GRASS have been developed by scientists and are based on published methods and concepts. Together with its many years of active deployment, it is this transparency which allows for the rigour of critical review and the quality assurance, upon which credibility of GRASS is founded. References to relevant literature are provided in the software documentation where appropriate. Since the GRASS community is a highly responsive environment, new functionality, e.g. an only recently published algorithm or method, can be implemented immediately in the development version or as an add-on, but has to undergo extensive testing and quality control before it will be available in the next official stable release.

3. Software capabilities

GRASS GIS 6.4.1, the current stable release, is the result of more than 9000 software enhancements and fixes with respect to the previous stable release 6.2.3. All changes are tracked in a public source code repository, along with a real-time notification system through email, IRC postings, and an automated and annotated online change log (Antoniol et al., 2003; Di Penta et al., 2005). Based on this, instant peer review is performed by a group of developers and other interested parties. GRASS is written in POSIX-conforming ANSI C with some functions written in the C++ and Python programming languages.

The recently published version 6.4 release offers two highly visible developments to the user experience, including a new modern Graphical User Interface (GUI) with an integrated location wizard (to define the project database and projection parameters), vector digitizer, SQL query builder, attribute editor, model builder, 3D view mode, and georeferencing tool including full native support for Microsoft Windows (2000, XP, Vista, and Windows7). The new native GUI is written in the Python programming language using the wxPython toolkit (Landa et al., 2008). As before, UNIX based platforms (GNU/Linux, Mac OSX, BSD, etc.) continue to be actively supported, as the source code base is portable. In addition, a first mobile solution for operating GRASS on handheld devices with real-time support through Wifi and voice control was demonstrated in (Stankovic et al., 2004). The graphical user interface and messages have been fully or partially translated into over 20 languages, including numerous European, Arabic, Japanese, Vietnamese, and other East Asian languages (Masumoto et al., 2005).

An extensive set of map projections and geodetic datums are supported with the ability to select interactively from standard map projections, to define custom parameters, to take projection parameters directly from georeferenced input data, or to select projection identifiers from the standard EPSG projection database (http://www.epsg-registry.org). GRASS expands on the pioneering PROJ.4 library (http://proj.osgeo.org) for much of this support and includes a number of georeferencing wizards and reprojection tools. Furthermore, some shortfalls in the current PROJ.4 concept for geodetic datum handling are overcome by internal extensions. The concept of the GRASS project database (known within the software as "locations", see Fig. 1) employs a strict single-location/

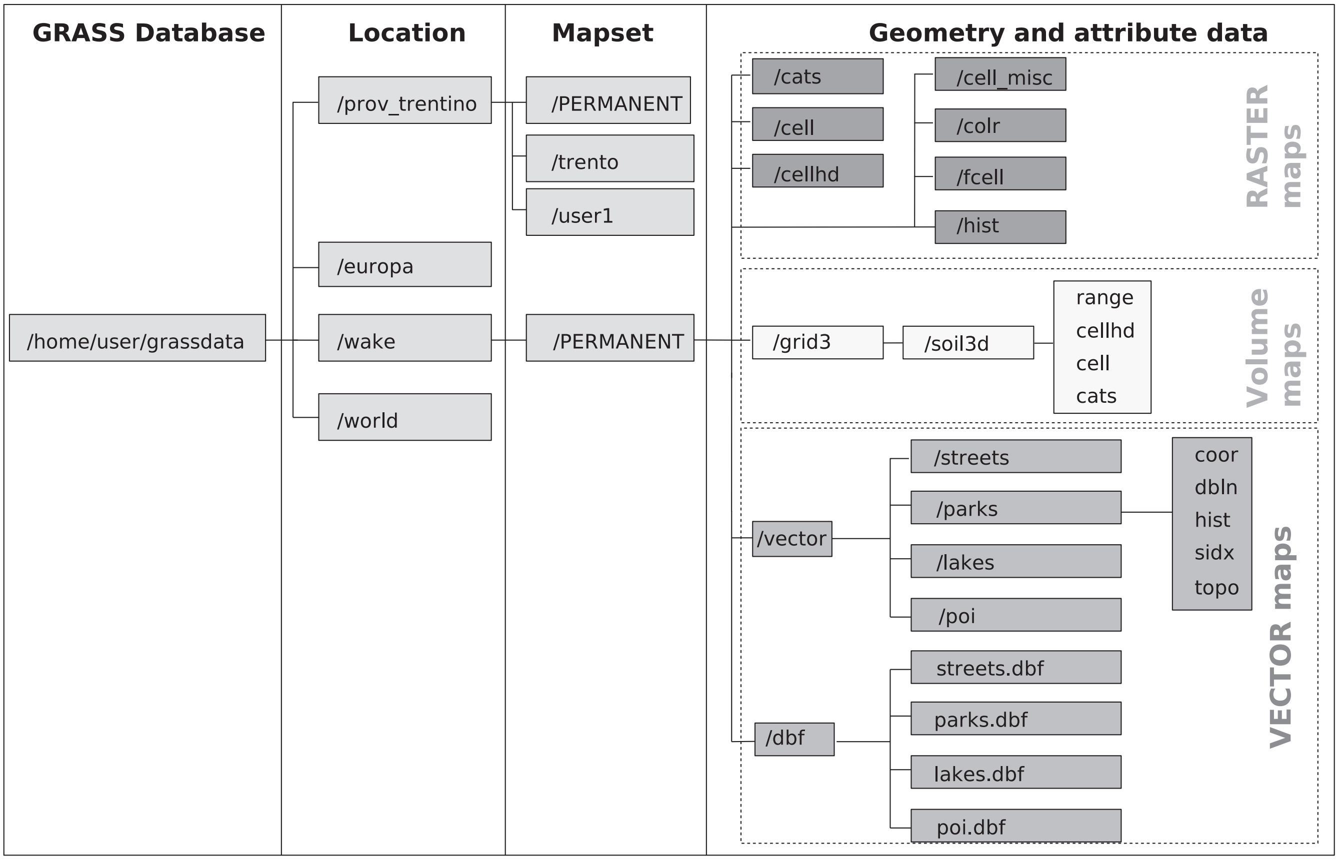

Fig. 1. Structure of GRASS GIS project data base ("location").

single-projection system paradigm for projections and coordinate systems resulting in a more robust workflow. Within a "location", simultaneous access by several users is supported, enabling, for example, teams to collaborate on the same project over a network without the danger of overwriting each others' work.

Interoperability with the majority of common GIS data formats is granted through the GDAL/OGR library (http://www.gdal.org). This Open Source library supports an extensive range of raster and vector formats, adhering to the OGC-conforming Simple Features specifications for vector data handling, and it has been adopted into a wide range of popular open and proprietary GIS software packages and virtual globes which greatly facilitates data exchange between different GIS environments. Additionally, GRASS allows import from OGC Web Services protocols (WMS and WFS), and output to graphical formats (PNG, TIF, PostScript or PDF). GRASS is one of a very few GIS suites to offer a fully-featured 3D visualization engine, NVIZ (Hofierka et al., 2002), with single and multi-map 2D perspective support but also voxel visualization as isosurfaces or cutting plane rendering, animation, full resolution exports for posters, and 3D query. Furthermore, GRASS can be linked directly to several software applications including Quantum GIS, Sextante (an analytical extension for gvSIG), statistical and geostatistical support (R Statistical Computing Environment, gstat, MATLAB), and rendering and multi-dimensional visualization software (Furlanello et al., 2003; Bivand et al., 2008; Neteler et al., 2008). GRASS also provides an SQL interface to various database engines and even a simple SQL wrapper around DBF files. Supported database engines with true SQL are PostgreSQL, MySQL, and SQLite, in addition to ODBC-connected databases. There are various possibilities to interface GRASS and R for statistical and geostatistical analysis in R. For newcomers to GRASS GIS, the Quantum GIS (QGIS, http://www.qgis.org) interface is of particular interest since the integrated GRASS toolbox allows users to access a wide range of GRASS functionality (Sherman, 2008). Selected examples of GRASS capabilities are 3D visualization, surface interpolation, cartography, terrain analysis, georeferencing, reprojection, image classification, hydrological and erosion modelling, LiDAR point cloud processing, and voxel processing. The underlying concept is to integrate GRASS as a GIS backbone in existing frameworks.

4. Design and technical developments

GRASS is written in a fully modular way which minimizes overhead (Fig. 2). This allows users to run the system, or parts of it, even in portable smart devices with limited RAM (Stankovic et al., 2004), or effectively scale it up to process massive datasets which exceed available system memory by orders of magnitudes. The latest stable release provides 425 modules for data management and analysis. These are organized firstly by category (general GIS management modules: g.*, vector modules: v.*, raster modules: r.*, 3D raster modules: r3.*, image processing: i.*, database management: db.*, cartography modules ps.*, etc.) and secondarily by function ("in" input modules, "out" output modules, "cost" cost surfaces, "network" network analysis, etc.). This categorization helps the user to navigate easily in the wealth of available tools, also supported by a tree based functionality catalogue in the graphical user interface. Table 1.

GRASS can be run fully automated on high performance computing clusters. The usage of GRASS on a cluster has been demonstrated by (Neteler, 2010; Neteler, 2005) for MODIS satellite sensor time series processing. Geospatial data processing can be deployed in batch mode by sending each job to the job management

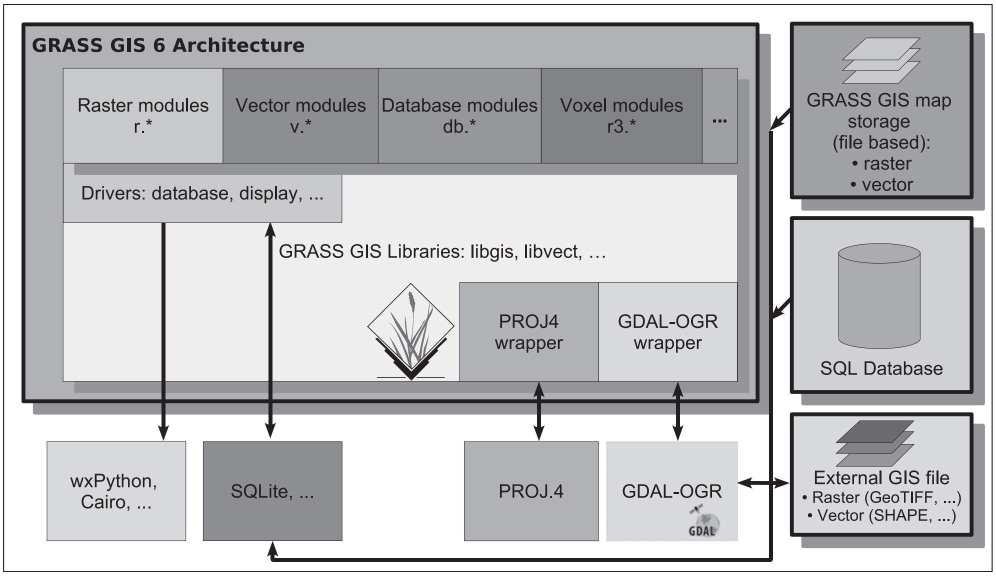

Fig. 2. Architecture of GRASS GIS 6.4: Core system, related libraries and external file/database support.

software's queue. The job scheduler then load-balances the available cluster nodes. Results are written back into the GRASS database which, in this case, is typically on a network drive visible to all nodes. No special GRASS modifications are needed to analyse massive datasets in parallel. A simple parallelization can be obtained by either elaborating the data in chunks and merging the results, which can easily be achieved by adjusting the computational region, or by processing the data on a map-by-map basis in the case of time series data. Published examples for parallelized GRASS software and GRASS usage in grid computing are (Huang et al., 2007; Sorokine, 2007; Silva, 2010). Support for cloud computing is under active development and planned for the next major release of GRASS. Ongoing development concentrates on GRASS 7, which already provides improved display, raster and vector engines with even better scalability for massive datasets and cross-platform compatibility. Support for the OGC Web Processing Service (WPS) has been implemented in the parser, i.e. the resulting WPS-XML descriptions can be directly used in WPS frameworks like pyWPS (http://pywps.wald.intevation.org), 52N (http://www.52n.org) or ZOO (http://www.zoo-project.org). These developments have already lead to an increased usage of GRASS as a GIS backbone in Web Services (Li et al., 2010; Müller et al., 2010).

Almost all GRASS modules in the current release have a non-interactive mode allowing full control of the GIS from Python, Perl, UNIX shell scripts, and DOS batch files. Such scripts or batch files can chain several modules together in a customized workflow and can also be used for batch processing, e.g. automated import, cleaning, and resampling of a number of time series maps within one script. The GRASS parser is able to render module usage and control descriptions as HTML, XML, or Tcl/Tk output. An assortment of low-level geoprocessing modules and a number of script-specific caretaker modules are provided to aid the writing of these user scripts. These tools allow for simple and fast deployment of new GRASS modules including full module infrastructure support and an automatically generated interactive Tcl/Tk or wxPython GUI dialogue. This has led to a large number of community contributed add-on modules, with more than 100 user supplied extensions available on the community help site (http://grass.osgeo.org/wiki/Addons).

A new Python scripting library has also been added which gives access to many common GIS library tasks, greatly enhancing and simplifying access to powerful and streamlined geospatial and workflow functions. Furthermore, a Python front-end is offered to the mature and extensive C libraries for advanced programming. The GRASS developers maintain extensive user documentation and a programmers' manual (http://grass.osgeo.org/programming6/) in order to stimulate and support new developments. New developments are also sponsored by Google's Summer of Code programme in which for a period of three months selected students are financed in order to program new functionality for GRASS and other Open Source software projects. Several of these contributions have meanwhile been integrated into the main GRASS suite after a final source code auditing. Additionally, a number of existing modules have been improved in terms of both accuracy and processing performance.

Table 1
GRASS GIS command structure.

Prefix	Function class	Type of command
d.*	display	graphical output
db.*	database	database management
g.*	general	general file operations
i.*	imagery	image processing
m.*	misc	miscellaneous commands
ps.*	postscript	map creation in Postscript format
r.*	raster	2D raster data processing
r3.*	3D raster	3D raster data processing
v.*	vector	2D and 3D vector data processing

5. Environmental applications

Due to the scientific background of many of its contributors, and its historical background, GRASS is well equipped for environmental modelling, and at the same time it retains the usefulness for a multi-purpose GIS environment.

The following two case studies illustrate the use of GRASS in the field of public health, epidemiology, and infectious diseases. Many continents, including Europe, are facing an increasing risk of introduction or spread of tropical vector-borne diseases transmitted by insects, ticks and rodents threatening human and animal health (Senior, 2008). This risk is driven by environmental and socio-economic changes.

In a case study, Rizzoli et al. (2007) assessed new human cases of tick-borne encephalitis (TBE) in the province of Trento in northern Italy, in order to predict the highest risk areas for increased TBE virus activity. The authors used GRASS to correlate spatial serological data from domestic goats to the autumnal cooling rate calculated from Moderate Resolution Imaging Spectroradiometer (MODIS) land-surface temperature (LST) data. They found a significant relationship between the autumnal cooling rate and the presence of antibodies against the virus in serum of goats. This virus seroprevalence in goats was then correlated with human TBE occurrence and tick bites. The autumnal cooling rate from MODIS LST showed predictive power for the subsequent year, being useful as early-warning predictors of TBE risk in humans.

Another study assessed the ongoing expansion of the tiger mosquito (*Aedes albopictus*), a vector of several emerging diseases (Roiz et al., 2011; Neteler, 2011; Neteler et al., 2011). In order to identify the areas currently most suitable for the occurrence of the tiger mosquito in the Province of Trento (Italy), field entomological observations were combined with analyses of satellite temperature data (MODIS LST) and human population data. The geocoded trap data were managed in GRASS. The human population density and distance to human settlements were extracted at the trap positions, as well as temperature indicators obtained from MODIS LST data. Threshold conditions were determined for the survival of overwintering eggs and for adult survival using both January mean temperatures (0 °C LST) and annual mean temperatures (11 °C LST). These values were the best predictors for identifying the areas that could potentially support populations of the tiger mosquito. Prior to data extraction, more than 11,000 daily MODIS LST data were gap-filled in GRASS since many scenes were cloud-contaminated or showed missing pixels due to other problems (Neteler, 2010). A temperature-gradient-based model was used for the map reconstructions. The final, completed LST map set was then aggregated to minimum and maximum temperatures to obtain January and annual mean temperatures and filtered by according thresholds. The resulting maps were integrated into a final map describing the suitability for mosquito survival and establishment (see Fig. 3), presented in Roiz et al. (2011).

Further applications using GRASS with a focus on analysing emerging infectious diseases have been published in the field of epidemiology and public health (Furlanello et al., 2003; Carpi et al., 2008). Machine learning in R was used by Furlanello et al. (2003) on top of GRASS to produce risk maps for exposure to Lyme borreliosis and tick-borne encephalitis in Trentino, Italy, taking advantage of the GRASS-R interfacing. Carpi et al. (2008) introduced the use of MODIS Land Surface Temperature data to the assessment of tick-borne encephalitis risk.

A number of studies have demonstrated that GRASS is a powerful tool in many research fields and scientific tasks within the domain of environmental science. For example, Löwe (2004) set up a severe weather information system for convective cells using rule-based expert systems to classify such convective clouds from radar data, another example where GRASS was chosen as GIS engine for automated processing. Villa and Costanza (2000) presented an integration of GRASS and modelling tools to support different modelling paradigms in the same simulation model where GRASS was also used as the GIS engine.

GRASS has been extensively used in terrain modelling since the 1990's (Cebecauer et al., 2002; Hofierka et al., 2009), leading to a rich toolset tailored for massive data analysis. Several photovoltaic applications have been published in the field of terrain and solar energy (Huld et al., 2006; Šúri et al., 2007; Hofierka and Kanuk, 2009). A dedicated solar energy module was included in GRASS and further used to quantify the absolute and relative time-dependent influence of landscape-scale physiographic factors in mediating regional temperatures (Dobrowski et al., 2009). Landscape structure analysis has also been implemented as a dedicated module set (Baker and Cai, 1992).

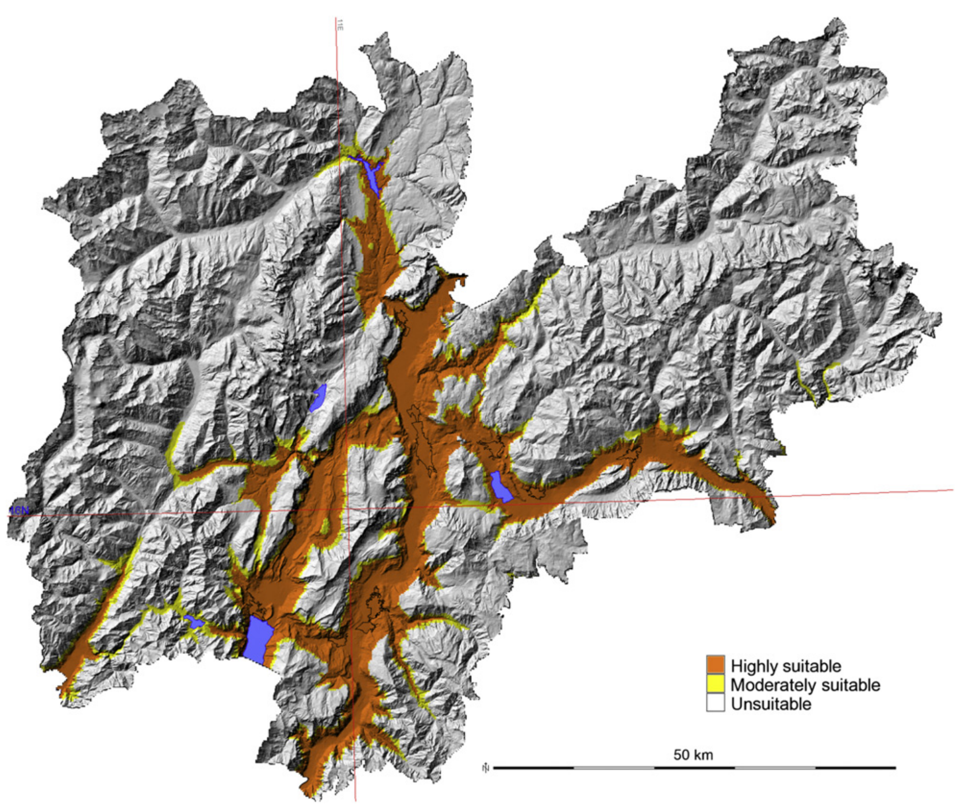

Fig. 3. Potential distributional areas of *Aedes albopictus* (tiger mosquito) in Trentino, Italy, based on an analysis with GRASS GIS, cited from (Roiz et al., 2011).

In the field of geology, Masumoto et al. (2004) presented the theory and implementation of geological 3D modelling of the hierarchical relationships between boundary surfaces and geologic units. The implementation was greatly facilitated by the generic 3D processing infrastructure existing in GRASS. As part of a comparative study of software in geomorphometry, Hofierka et al. (2009) showed how to compute DEMs from various data sources and how to derive local and regional land–surface parameters. Further geomorphometrical methods were presented in Grohmann (2004) and Grohmann and Riccomini (2009).

In an archaeological review paper, Lake and Woodman (2003) describe the theoretical background for the need of GIS-based methods on the example of a visibility study. The authors chose GRASS because of its modular structure and because Open Source Software is a facilitator for developing new methodology; the authors also provide an example of its application. Barton et al. (2010) studied long-term effects of varying landuse practices by subsistence farmers on landscapes by applying computational modelling to neolithic socio-ecological dynamics. In Rassmann and Ducke (2010), a method combining low-level GRASS modules was used to refine the calculated spread of neolithic tools across Europe, and has been compared favourably to methods available in other GIS suites.

In order to gain from complementary features, GRASS has been integrated with dedicated statistical software. Its linkage to R and the PostgreSQL database system with bidirectional data exchange is shown in Bivand and Neteler (2000), Bivand et al. (2008), and Carrera-Hernández and Gaskin (2006).Biagi and Negretti (2004) presented the integration of the gstat statistics program with GRASS for the analysis of stochastic processes. In the field of ecology, Garzon et al. (2006) presented a modelling framework for predicting forest areas by integrating a machine learning extension of R within GRASS for predictive habitat modelling of *Pinus silvestris* on the Iberian peninsula. The ISAMUD system for wildlife management integrates spatial databases with GRASS, using it to compute spatial statistics on locations, trajectories and home ranges from GPS collar wildlife data based on their environmental attributes (Cagnacci and Urbano, 2008). Ortigosa et al. (2000) presented the integration of a dedicated software tool for habitat suitability assessment with GRASS.

Regarding water and water availability as key environmental characteristics, Carrera-Hernández and Gaskin (2006) presented an integration of GRASS with the finite difference groundwater flow model MODFLOW. Mitasova et al. (2004) developed simulation tools in GRASS for overland shallow water flow and sediment transport using the path sampling method for solving the continuity equations describing mass flows over complex landscape surfaces. With regard to overland flow routing, flow accumulation, and stream network extraction, GRASS scales well even with very large datasets and it is able to produce realistic results also in difficult terrain (Metz et al., 2011), matching or exceeding the quality of alternative approaches. The support of raster 3D volumes (voxels) is not commonly found in desktop GIS. Using this technology in GRASS, Hofierka et al. (2002) presented precipitation map calculations based on volumetric splines for Slovakia.

A toolbox for LiDAR data analysis was presented by Brovelli et al. (2004). The development of this toolbox was greatly facilitated by the modular design of GRASS. This has subsequently become integral part of the main software package. It offers outlier and edge detection as well as DTM and DSM creation. Mitasova et al. (2009) computed a consistent series of high-resolution digital elevation models from LiDAR data using spline-based approximation in GRASS because it allows parameter optimization. In optical remote sensing, the ability of GRASS GIS to orthorectify aerial photographs has been described in detail in Rocchini et al. (2011) along with the theoretical background behind rectification.

GRASS also plays a relevant role in educational contexts, for example in online courses in developing countries where Free and Open Source solutions are especially relevant due to the costs of proprietary GIS software (Schweik et al., 2009). Within OSGeo, educational content is collected in a dedicated Web portal (http://www.osgeo.org/educational_content). Furthermore, for teaching GIS, ready-to-use GIS implementations can be easily tailored on a USB stick including data and other seminar materials. This avoids any installation tasks prior to teaching.

6. Conclusions

GRASS has become a high quality cutting edge GIS with an almost unparalleled depth of offering directly within the main software package. Its functionality has been influenced by its usage and evaluation in numerous scientific studies, a sample of which were described in the previous section, during the last two decades. The Open Source development model along with a free software license grants long term availability as the source code is offered on independent public Web sites. We consider the development of robust Open Source GIS software as important and relevant for several reasons: (i) quality algorithms due to public peer review, (ii) facilitation of customization, and (iii) good and fast support via email lists and Web forums (Cagnacci and Urbano, 2008; Steiniger and Hay, 2009).

The GRASS project represents a successful example of the collaborative development model. Users are encouraged to download the underlying code and inspect, evaluate, benchmark, customize, and enhance all algorithms and methods. Due to its vibrant user and development communities, we envision that GRASS will continue to be a general-purpose GIS with a continuously improved structure and strong support for local adaptation for specific needs, particularly with respect to environmental studies. Since it is a modular system (organized into libraries and application modules), it may be implemented in various environments ranging from academic systems to business and public administration usage with their varying requirements.

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