Free and Open Source Software for Geospatial Applications (FOSS4G) to support Future Earth

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The development, integration, and distribution of the information and spatial data infrastructure (i.e. Digital Earth; DE) necessary to support the vision and goals of Future Earth (FE) will occur in a distributed fashion, in very diverse technological, institutional, socio-cultural, and economic contexts around the world. This complex context and ambitious goals require bringing to bear not only the best minds, but also the best science and technologies available. Free and Open Source Software for Geospatial Applications (FOSS4G) offers mature, capable and reliable software to contribute to the creation of this infrastructure. In this paper we point to a selected set of some of the most mature and reliable FOSS4G solutions that can be used to develop the functionality required as part of DE and FE. We provide examples of large-scale, sophisticated, mission-critical applications of each software to illustrate their power and capabilities in systems where they perform roles or functionality similar to the ones they could perform as part of DE and FE. We provide information and resources to assist the readers in carrying out their own assessments to select the best FOSS4G solutions for their particular contexts and system development needs.

Keywords: open source software; geospatial software; FOSS4G; Future Earth; Digital Earth

1. Introduction

Future Earth (FE) is a 10-year international research initiative that emerged in 2011 to create a global environmental change research platform to provide more useful and accessible knowledge for decision-makers, and to support the acceleration of the transformation to a sustainable world (Future Earth Norway Secretariat 2015; Future Earth Secretariat 2013). FE focuses on three main research themes: Dynamic Planet; Global Sustainable Development; and Transformations Towards Sustainability (Future Earth Secretariat 2014). It is designed to provide a fundamental, holistic understanding of the interconnections between natural and human drivers of change, the resulting environmental changes, and their implications for human well-being (Future Earth

Secretariat 2013). These interactions take place across multiple spatial and temporal scales. Being a global effort, the development, integration, and distribution of the information envisioned to be part of FE will occur in very diverse technological, institutional, socio-cultural, and economic contexts around the world. This complex context and ambitious goals require to bring to bear not only the best minds, but also the best science and technologies available.

While FE is conceived as a global research platform for co-creating and co-developing knowledge, Digital Earth (DE) is the technological framework and infrastructure to realize the FE vision and goals. DE was conceived by Al Gore in 1998 as a multi-scale, multi-resolution, three-dimensional representation of the planet allowing students, scientists, policy-makers and all societal sectors to spatio-temporally navigate and manage georeferenced information (Gore 1998). Recently several authors have argued that, although a number of elements envisioned by Gore have become a reality, some gaps still exist and they propose a new conceptualization of DE more in line with the fast societal and technological changes (Annoni et al. 2011; Goodchild et al. 2012; Craglia et al. 2012; Brovelli et al. 2015a).

Among the multiple areas where collaboration will be needed to implement FE as a DE-based platform for strategic and integrated Earth system research, geospatial information science and technologies will be essential (Craglia et al 2012). More specifically, in this paper we argue that Free and Open Source Software (FOSS) for Geospatial Applications (FOSS4G) can play an important role in data collection, creation of components, integration of information systems, stakeholders' engagement, and dissemination of information that will be essential for the realization of the FE vision. The purpose of this paper is to present an overview of the diversity and sophistication of the FOSS4G software options, provide the readers with resources and

point to guidelines that can assist them in choosing FOSS4G solutions that match their specific needs and implementation contexts, and finally, illustrate how FOSS4G can contribute to achieve the FE seven key outputs.

FOSS4G are software that provides the user the freedom to run the program for any purpose, access the source code to study how it works and change it, redistribute copies, and redistribute copies of modified versions of the software (GNU Project 1996). The software must comply with the 10 criteria listed in the Open Source Initiative[1]. There is at least one mature sophisticated FOSS4G for every geo-technology area and geospatial information need and application, from data collection in the field, crowdsourcing, desktop applications, spatial extensions to Database Management Systems, to software stacks to create sophisticated Web-based systems using client-server architectures (Moreno-Sanchez 2012; Steiniger and Hunter 2012). Emerging technologies such as Unmanned Aerial Vehicles (UAV)[2] and Structure from Motion[3] are exceptions where the FOSS4G options do not have yet the maturity or robustness for routine deployment; however, several efforts exist such as OpenDroneMap[4] and MicMac[5], respectively. Currently there are over 350 FOSS4G projects listed in FreeGIS.org[6] and Open Source GIS[7]. Some of these projects have a history that dates back to the early 1980s (e.g. GRASS GIS[8]; Mitasova and Neteler 2004) while others are

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1

      http://opensource.org/docs/osd

2   https://en.wikipedia.org/wiki/Unmanned_aerial_vehicle

3   https://en.wikipedia.org/wiki/Structure_from_motion

4   http://opendronemap.github.io/odm

5   http://www.micmac.ign.fr

6 http://freegis.org
7 http://opensourcegis.org
8 http://grass.osgeo.org

more recent and yet have a wide and solid user base, such as Web-GIS platforms (Yao and Zou 2008).

The remainder of the paper is organized as follows. Section 2 provides an overview and categorization of FOSS4G solutions that can be used to address the geospatial information needs of FE. Section 3 discusses criteria for software selection and some of the challenges for adopting FOSS4G; the most common inhibitors and facilitators for FOSS4G adoption are listed. Section 4 presents several existing high-impact applications of FOSS4G related to the seven key focal outputs of the 2025 FE vision. Finally, Section 5 present conclusions and recommendations.

2. Addressing Future Earth geospatial information needs through FOSS4G solutions

The creativity, dynamism and high-profile success stories of FOSS/FOSS4G are attracting increasing attention from end users, developers, businesses, governments, educators and researchers around the world (e.g. Weber 2004; Walli et al. 2005; CRM-Reviews 2006; Faber 2007; Hall and Leahy 2008; Swain et al 2015; Nakayama and Mori 2012). Though findings are varied as to the strengths and weaknesses of FOSS/FOSS4G for specific technological, institutional, socio-cultural and economic contexts and purposes (Erlich and Aviv 2007; Ven and Mannaert 2008), today it is clear that FOSS/FOSS4G provide robust and reliable software besides private/proprietary/closed-source software solutions, and there are opportunities for mutual benefit and complementarity between these two software options for the development of large sophisticated applications (Moreno-Sanchez 2012).

FOSS/FOSS4G have been declared crucial for developing countries because they enable them to develop their own technology instead of having to import it, provide a path to close the digital divide, and can be the base for creating their Spatial

Data Infrastructures (SDI) in a context where resources for system development and maintenance are scarce (Naronha 2002, 2003; Rajani et al. 2003; Schenker 2003; Wambui 2004; Holmes et al. 2005; Camara and Fonseca 2007; Moreno-Sanchez 2012; Molina and Bayarri 2011). Developed countries are also increasingly using FOSS4G solutions for different reasons (e.g. Marson 2005; Kaneshige 2008; Gillespie 2000; Lettice 2004; Coonan 2004). In both development contexts, FOSS4G fosters creativity, provides healthy competition to private/proprietary/closed-source software, may lead to affordable pricing and increased access, addresses some national security concerns, and reduces dependency on foreign technology.

FOSS/FOSS4G and DE/FE have one important thing in common, the creation, maintenance, and development of both are based on a philosophy of openness, sharing, collaboration and distributed development. This point can not be underestimated. The way technology and its use are approached have broad and deep impacts on the organization and people that use it. If the spatial components of DE and FE are based on technologies that align with the philosophy and spirit of the systems and goals they support, they can have important benefits in fostering a culture of openness, sharing and collaboration (Hippel and Krogh 2003; Stewart and Gossain 2006).

Several overviews and classifications of FOSS4G exist (e.g. Sanz-Salinas and Montesinos-Lajara 2009; Steiniger and Bocher 2009; Steiniger and Hunter 2012 and 2013). Here we concentrate on presenting some mature FOSS4G that can be used to work on the DE technological developments proposed by Craglia et al. (2008) as fundamental to realize the FE vision: 1) Organizing geographic information (related to storing and accessing geodata); 2) Geography as a way to organize information (related to Web-based geo-visualization and geo-processing); 3) Geosensing the world (related to geodata acquired from sensors, including citizen sensors); and 4) Innovation in

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supporting technology (related to general computing technology and hence not addressed here). Table 1 lists these needs/functions and examples of some well-known mature FOSS4G that can be used to address them. The list of FOSS4G is not meant to be comprehensive. The software listed is mature, well know, and with record of successful applications as illustrated in Section 4.

Table 1. Future Earth major functions/needs with the corresponding software category and examples of FOSS4G projects that can be used to address them.

Area related to FE function/need	Software function	FOSS4G category	FOSS4G examples
Organizing Geographic Information	Desktop visualization and basic analysis	Desktop GIS	QGIS, gvSIG, uDig, OpenJUMP, SAGA
	Geodata storage	Spatial Database Management Systems (DBMS)	PostgreSQL/PostGIS, SQLite/SpatiaLite, MySQL Spatial, MongoDB, CouchDB, Rasdaman
	Geodata analysis and processing	Desktop geoprocessing and analysis tools	GRASS GIS, R, CyberGIS Toolkit
	Serving geodata over the Web	Web-based GIS (e.g. OGC Web Services OWS)	GeoServer, MapServer, QGIS Server, deegree
	Cataloguing geodata	Web-based catalogue services (e.g. OGC Catalog Services for the Web CSW)	GeoNetwork, pyCSW
Geography as a way to organize information	2D Web visualization	2D Web clients	OpenLayers, Leaflet
	3D Web visualization	Virtual Globes	NASA World Wind, Cesium, WebGL Earth, OpenWebGlobe
	Web-based geoprocessing	Web-based geoprocessing (e.g. OGC Web Processing Services WPS)	pyWPS, ZOO, 52°North WPS, GeoServer, deegree

Geosensing the World	Geo-referenced data collection from specialized sensors	Integration, processing and distribution of sensor data (e.g OGC Sensor Observation Services SOS)	istSOS, 52°North SOS
	Geo-referenced data collection from mobile devices and sensors (including citizen sensors)	Mobile and geocrowdsourcing tools	Geopaparazzi, Open Data Kit (ODK)

The first area in Table 1 column 1 includes FOSS4G applications able to prepare, store, process, catalog and Web publish geodata. Visualization and basic analysis can be performed using desktop GIS software such as QGIS[9], gvSIG[10], uDig[11], OpenJUMP[12] and SAGA[13]. Complex data processing, raster modeling, and statistical analyses can be done using more advanced tools like GRASS GIS[14], R[15] and the CyberGIS Toolkit[16]. Spatial extensions to Database Management Systems (DBMS) enable them to store geodata and apply a growing number of spatial analytical functions to vector and raster data sets. PostGIS[17] extends PostgreSQL[18], SpatiaLite[19] extends SQLite[20] DMBS and MySQL implements spatial extensions[21].

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9 http://qgis.org
10 http://www.gvsig.com
11 http://udig.refractions.net
12 http://www.openjump.org
13 http://www.saga-gis.org
14 https://grass.osgeo.org
15 https://www.r-project.org
16 http://cybergis.cigi.uiuc.edu/cyberGISwiki/doku.php/ct
17 http://postgis.net
18 http://www.postgresql.org
19 https://www.gaia-gis.it/fossil/libspatialite/index
20 http://www.sqlite.org
21 http://dev.mysql.com/doc/refman/5.7/en/spatial-extensions.html

No-SQL DBMS like MongoDB[22] and CouchDB[23] and multi-dimensional array

databases like Rasdaman[24] also offer capabilities for the storage and management of

geodata. Finally, powerful SDI can be created through OGC-compliant FOSS4G tools

for serving geodata over the Web (GeoServer[25], MapServer[26], deegree[27] and QGIS

Server[28]) and cataloguing geodata (GeoNetwork[29] and pyCSW[30]).

Visualization of geodata on the Web is a relatively new field, but it has grown

rapidly in recent years (Minghini 2014). Mature FOSS4G products in this area include

2D Web clients built using OpenLayers[31] and Leaflet[32] JavaScript libraries. In the 3D

Web Virtual Globes such as NASA World Wind[33], Cesium[34], WebGL Earth[35] and

OpenWebGlobe[36] offer powerful platforms for development (a recent overview of

Virtual Globes is provided by Brovelli et al. 2013a). Web-based geoprocessing

capabilities are also growing rapidly, in this area FOSS4G technologies implementing

the reference OGC Web Processing Services (WPS[37]) standard include pyWPS[38],

ZOO[39], 52°North WPS[40] and again GeoServer and deegree.

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22 https://www.mongodb.org
23 http://couchdb.apache.org
24 http://www.rasdaman.com
25 http://geoserver.org
26 http://mapserver.org
27 http://www.deegree.org
28 http://docs.qgis.org/2.2/en/docs/user_manual/working_with_ogc/ogc_server_support.html
29 http://geonetwork-opensource.org
30 http://pycsw.org
31 http://openlayers.org
32 http://leafletjs.com
33 http://worldwind.arc.nasa.gov/java
34 https://cesiumjs.org
35 https://www.webglearth.com
36 http://www.openwebglobe.org
37 http://www.opengeospatial.org/standards/wps
38 http://pywps.org
39 http://www.zoo-project.org
40 http://52north.org/communities/geoprocessing/wps

The last area in Table 1 column 1 includes applications for managing geodata collected by sensors, including both instrument sensors and citizens who act as human sensors (Goodchild 2007). The OGC Sensor Web Enablement (SWE, Botts et al. 2008) allows to process all sensor-like information thanks to a number of standards, these include Sensor Observation Service (SOS[41]), whose main FOSS4G implementations are istSOS[42] and 52°North SOS[43], and the new OGC candidate standard SensorThings API[44] (Open Geospatial Consortium 2015) for managing IoT devices, data, and applications over the Web. This is a new field of application and no mature FOSS4G implementation exists yet. Software for collecting and managing geodata from mobile devices will also play an important role in realizing the vision of FE, prominent examples are Geopaparazzi[45] and the Open Data Kit (ODK)[46] suite, Brovelli et al. (2016) demonstrate how they can be used in mobile data collection.

The category of geospatial frameworks is gaining importance. Applications of this kind are not included in Table 1 because they typically consist of combinations of other software products such as: DBMS, geodata servers, geocataloges and Web clients. A notable mature FOSS4G product in this category is GeoNode[47] based on a powerful software stack that includes PostGIS, GeoServer, GeoNetwork and OpenLayers. It is an SDI-oriented collaboration platform to upload, edit and share geospatial data and maps. After login authentication users can rate and comment maps, thus creating a collaborative platform. A second example is PoliCrowd[48] (Brovelli et al. 2014), based on NASA World Wind and other FOSS4G products (e.g. PostgreSQL, GlassFish and

41 http://www.opengeospatial.org/standards/sos
42 http://istsos.org
43 http://52north.org/communities/sensorweb/sos
44 http://ogc-iot.github.io/ogc-iot-api/index.html
45 http://geopaparazzi.github.io/geopaparazzi
46 http://opendatakit.org
47 http://geonode.org
48 http://geomobile.como.polimi.it/policrowd2.0

ODK). It is a multi-thematic and multi-dimensional social platform focused on citizen-sensed data.

Big Data (see Yangyon and Yun 2015 for definition) is a theme that will cut across all the areas in Table 1. Although beyond the scope of this paper, it is worth mentioning that there are mature FOSS for the collection, storage, processing, analysis, transferring and aggregating of Big Data[49]. FOSS4G code libraries (e.g. GDAL/OGR[50], GeoTools[51] and Proj4J[52]) have been also excluded from this overview, but readers must be aware that they are commonly used in all the software categories listed in Table 1. Section 4 will describe a number of large and/or sophisticated real-world implementations of all the software mentioned.

3. Software selection and challenges for adoption of FOSS4G in the context of Future Earth

Column 3 in Table 1 lists only a sample of FOSS4G options for each niche and geospatial information need that will be part of FE. The number of FOSS4G software options is large, diverse, and rapidly changing (e.g. some of the most frequently used are listed by Holmes et al. 2005; Bruce 2007; Sanz-Salinas and Montesinos-Lajara 2009; Steiniger and Bocher 2009; Garbin and Fisher 2010; Tsou and Smith 2011; Steiniger and Hunter 2012, and 2013; OSGeo-Live DVD[53]). The development of FE components will be done in very diverse contexts and conditions. The best FOSS4G solution depends not only of the capability of the software to perform needed tasks at a desired level of performance, but also on the specifics of the technological, institutional, socio-cultural and financial contexts, as well as the backgrounds and levels of expertise

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49 http://www.datamation.com/data-center/50-top-open-source-tools-for-big-data-1.html
50 http://www.gdal.org
51 http://geotools.org
52 https://github.com/Proj4J/proj4j
53 http://live.osgeo.org/en/index.html

of the personnel that will develop and maintain the system. Hence, it is difficult to list one or two FOSS4G recommendations for each FE informational need or application. We consider that a more useful approach is to provide the readers with information that will assist them to do their own evaluations and come up with the best FOSS4G solution for their specific context and FE development needs.

FOSS/FOSS4G solutions for FE systems development should be rigorously evaluated at par with private/proprietary/closed-source software in terms of their technical features, reliability, ease of use, documentation, technical support, customizability and extensibility, costs of training, total cost of ownership, support and maintenance, and management requirements (e.g. budget, in-house development team expertise, long-term maintainability) (see Wang and Wang 2001; Woods and Guliani 2005; Ven et al. 2008; Fitzgerald 2011; Chen et al. 2010). Besides these criteria, the evaluation of FOSS4G should include the following nine criteria proposed by the Open Source Geospatial Foundation (OSGeo[54]). OSGeo has developed guidelines for software development[55]; evaluation criteria[56]; and graduation as a high quality sustainable software[57]: 1) Open source software is already reasonably mature (working quality code); 2) Project already has a substantial user community; 3) Project already has a substantial and diverse developer community; 4) Project members are aware of, and implement support for, relevant standards (e.g. Open Geospatial Consortium, World Wide Web Consortium, International Organization for Standardization); 5) Project has linkages with existing OSGeo projects; 6) Project fills a gap related to software that OSGeo supports; 7) Project is prepared to develop in an open and collaborative fashion; 8) Project has contributions and interest from more than just one company/organization

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54 http://www.osgeo.org/content/foundation/about.html
55 http://www.osgeo.org/incubator
56 http://www.osgeo.org/incubator/process/evaluation.html
57 http://www.osgeo.org/incubator/process/project_graduation_checklist.html

(see e.g. OSGeo software metrics[58]); 9) Project is willing to migrate some or all of its infrastructure (code repository, web site, wiki, mailing list, etc.) to OSGeo support infrastructure, and to adopt a website style consistent with the foundation.

Also, Steiniger and Hunter (2013) present an extensive list of criteria that can be used to evaluate FOSS4G prioritizing them based on the software intended final use (business, research, or teaching). These authors also propose the following FOSS4G evaluation process based on several well-known and tested approaches to software evaluation and adoption: a) Develop software use cases for own context (or "user stories" as used in Agile software development); b) Establish a set of evaluation criteria based on the use cases; c) Perform the software evaluation with respect to the established criteria; d) Develop a weighting criteria according to application context (note, weighting is intended to be flexible so as to allow for different contexts); e) Select the software based on results of the evaluation and weighting scheme.

Several socio-cultural, economic, technological, and organizational issues have been identified as inhibitors or facilitators for the adoption of FOSS/FOSS4G (Giera and Brown 2004; Valimaki et al. 2005; Woods and Guliani 2005; Moreno-Sanchez et al. 2007; Morgan and Finnegan 2007; Viorres et al. 2007; Meeker 2008; Ellis and Van Belle 2009; Hauge et al. 2010; Nagy et al. 2010). Without being comprehensive lists and based on these authors, here are some we consider are more likely to emerge as part of FE developments. **Inhibitors:** a) Lack of awareness of software existence, relevance, or successful implementations, shortage of technical knowledge needed to implement and use it; b) organization has a favourable arrangement with a proprietary vendor (e.g. discounts; training or support); c) big/expensive prior investments in proprietary software infrastructure, changing operating model can be problematic; d) staff

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58 http://live.osgeo.org/en/metrics.html

resistance due to fear of being deskilled if using FOSS4G instead of commercial packages; e) shortage of providers, expertise, and traditional support; f) customization needs; g) lack of clarity on licensing issues; h) hidden costs (e.g. training and configuration; premium professional support; need to dedicate resources to community participation). **Facilitators:** a) FOSS4G technological/costs benefits outweigh its disadvantages/concerns; b) availability of FOSS4G-literate personnel; c) top management support for FOSS4G; existence of a committed and respected FOSS4G in-house champion; d) limited financial resources ensure FOSS4G consideration; e) FOSS4G can help bridge countries' cross-border technological and budgetary disparities and facilitate cooperation.

Much progress has been done in recent years to address some the inhibitor issues and enhance the facilitator ones. Major FOSS4G community groups and initiatives are enhancing awareness, facilitating access to support materials and education, establishing best practices, designing systematic approaches to ensure software can be trusted, assessing software integrity and security, and sharing successful implementation experiences (e.g. "GeoForAll" international network of FOSS4G labs[59]; Geoacademy[60]; The Open Source Observatory Europe[61]; EU-Free and Open Source Software Auditing Project[62] and the EU CASCADOSS project[63]).

4. Example of FOSS4G-based system

In this section we present how FOSS4G applications are related to the outputs of the FE 2025 vision described by the Future Earth Secretariat (2014). We use the spatial information system architecture depicted in Figure 1 to illustrate the following

59 http://www.geoforall.org
60 http://fossgeo.org
61 https://joinup.ec.europa.eu/community/osor/home
62 https://joinup.ec.europa.eu/node/148101
63 http://www.gisat.cz/images/upload/7abfb_cascadoss-flyer-en.pdf

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presentation. It is based on the three DE technological areas proposed by Craglia et al. (2008) and used in Section 2 to classify FOSS4G technologies: Organizing Geographic Information, Geography as a way to organize information, and Geosensing the World. Instead of one or few pieces of software which perform multiple functions (typical of proprietary solutions), system architectures based on FOSS4G are modular, composed of multiple software and technologies interacting with each other through the use of open standards and open formats. In Figure 1 the seven key focal outputs of the 2025 FE vision are noted in boxes (some of them are shortened for space reasons). The position where they are placed in Figure 1 relates to the FOSS4G class that is best suited to contribute to its implementation.
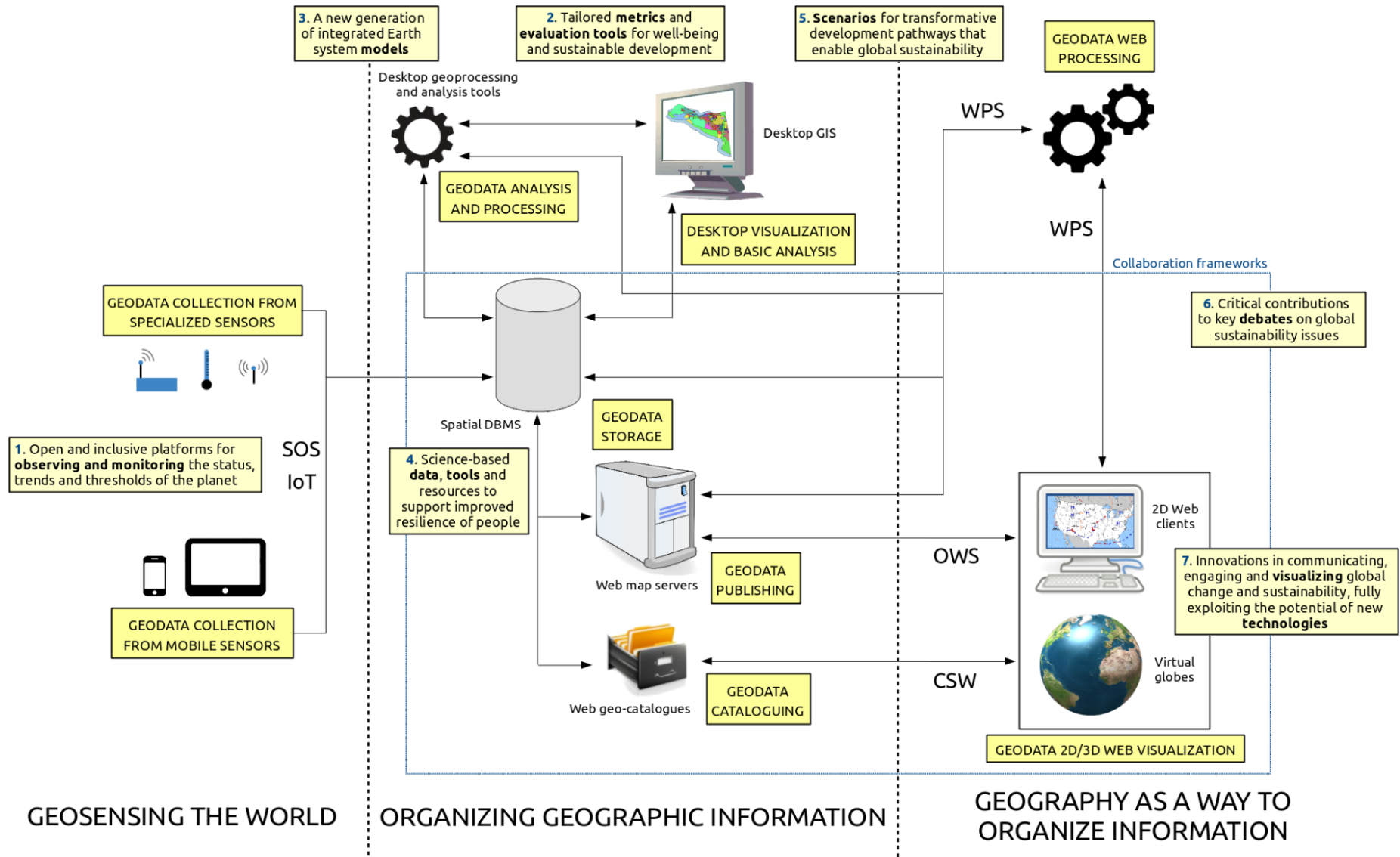
Figure 1. Architecture of a spatial information system to illustrate how FOSS4G can contribute to the achievement of the seven FE key focal outputs.

The following subsections present examples of real-world, high-impact FOSS4G applications related to each of the seven FE key outputs noted in Figure 1. The purpose is to illustrate the suitability and capability of FOSS4G to fulfill the needs and requirements of FE.

4.1 Open and inclusive platforms for observing and monitoring the status, trends and thresholds of the planet in a timely manner at different scales, including tracking fast-changing sentinel processes and systems

This FE need is addressed by systems that support the collection, storage, management, analysis and reporting of environmental data in real-time or almost real-time. Such systems can be fully based on FOSS/FOSS4G software options. This area primarily includes FOSS4G applications for managing observations collected from monitoring sensors. For instance, istSOS has been used in the EU ENORASIS project[64] as the basis of a Decision Support System (DSS) to optimize irrigation management by farmers and water management organizations (Cannata and Antonovic 2015a). It is also used in the Integrated Management of Red River System (IMRR) project to manage observational data collected by sensors in the Red River Basin (Vietnam)[65] for the purpose of visualizing, analyzing, and comparing different planning alternatives for the management of the river water system (Arias et al. 2015). 52°North SOS implementation is used to report air quality data from different European member states to the European Environment Agency (EEA) with the purpose of improving the flow of near-real time air quality data across Europe (Jirka et al. 2015). 52°North Sensor Web

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   http://enorasis.eu
65 http://tinyurl.com/jq8427j

tools are also applied in the field of oceanography to build ocean observatories, such as in the NeXOS[66], ODIP II[67] and FixO3[68] EU projects (Jirka et al. 2014).

There are also several FOSS4G crowdsourcing tools that allow a real-time sensing of our planet. ODK is been used by: the Amazon Conservation Team[69] to monitor deforestation in the Amazon; the African Soil Information Service[70] to map soil conditions; the Harvard Humanitarian Institute[71] to document human rights violations; the Haiti Regeneration Initiative[72] to monitor agricultural practices, crop productivity, and farmer yields of crops; and D-tree[73] to identify and treat severely malnourished children in a UNICEF-funded project. Brovelli et al. (2015b) exploit ODK in a number of projects related to urban planning. Projects based on Geopaparazzi include the development of the Disaster Management Information System of Osaka City[74]; Gasdroide[75], a system for CO_2 monitoring through the link between Geopaparazzi and an ad hoc sensor; Trackoid[76], a mobile application for realtime fleet and rescue teams coordination; and support for forest field surveys for the Japanese forestry governmental agency[77]. Finally, despite being a desktop GIS uDig was installed on the portable computers of FAO personnel carrying out agricultural monitoring activities in remote locations[78].

66 http://www.nexosproject.eu
67 http://www.odip.eu
68 http://www.fixo3.eu
69 http://www.amazonteam.org
70 http://africasoils.net
71 http://hhi.harvard.edu
72 http://www.haitiregeneration.org
73 http://www.d-tree.org
74 http://tinyurl.com/gwqnocg
75 https://bitbucket.org/moovida/gasdroide/wiki/Home
76 http://www.trackoid.eu
77 http://www.slideshare.net/KouichiKita/qgisgis
78 http://www.refractions.net/expertise/casestudies/2005-12-unfao/

Web platforms offering real-time monitoring of the Earth can be also included in this area. The monitoring platform of polar regions and cryosphere, maintained by Polar View[79], is a notable example of the use of GeoServer for seamlessly providing large volumes of data[80], including EO data. GeoServer and OpenLayers are also used within the EUMETSAT map viewer[81] offering weather and climate monitoring from space, and within the LaMMA geoportal[82] which provides global, real-time weather observations.

The area of Big Data is not covered in this paper. However, the collection, storage, manipulation, analysis and distribution of very large volumes of spatial data will be important activities as part of DE and FE. The CyberGIS[83] project aims to establish a fundamentally new software framework via a seamless integration of cyberinfrastructure, GIS, and spatial analysis/modeling capabilities. Part of this project is the CyberGIS Toolkit[84], a suite of loosely coupled open-source geospatial software components that provide computationally scalable spatial analysis and modeling capabilities enabled by advanced cyberinfrastructure.

4.2 Tailored metrics and evaluation tools for well-being and sustainable development

This FE output requires the combination and analysis of socio-economic and environmental data coming from diverse sources to generate metrics and indicators of well-being and sustainable development. Systems that incorporate database management systems with spatial extensions such as PostgreSQL-PostGIS, desktop GIS systems such as QGIS or GRASS GIS, and custom analytical software can be used as platforms to seamlessly integrate and analyze this diverse information. Then other

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79 http://www.polarview.org
80 http://www.polarview.aq
81 http://eumetview.eumetsat.int/mapviewer
82 http://geoportale.lamma.rete.toscana.it/MapStore/public
83 http://cybergis.cigi.uiuc.edu/cyberGISwiki/doku.php
84 http://cybergis.cigi.uiuc.edu/cyberGISwiki/doku.php/ct

FOSS4G can be used to provide access and distribute the information over the Web (e.g. GeoServer, OpenLayers). An important example is the EU Recharge Green project[85], which has developed a DSS using GRASS GIS and a QGIS plugin (Garegnani et al. 2015) to study the impact of exploiting renewable energy sources in the Alps. GRASS GIS was also used within the SOLAREC (Photovoltaic and solar electricity) EU project[86], aimed at implementing renewable energy in the EU as a sustainable and long-term energy supply. The Photovoltaic Geographical Information System (PVGIS)[87] provides a map-based inventory of solar energy resources and assessment of the electricity generation from photovoltaic systems (Šúri et al. 2007). The project WebGIS[88], fully based on GRASS GIS, implements the solar radiation model (Hofierka and Šúri 2002) to compute the photovoltaic potential on Europe. The Pakistan Agriculture Information System[89], which integrates many FOSS4G packages such as GeoServer, GeoNetwork and OpenLayers, provides a rich set of analyses and geoprocessing of data of Pakistan's crops and agro-meteorological variables. Similarly, the Global Atlas for Renewable Energy of IRENA (International Renewable Energy Agency)[90], is based on GeoServer and OpenLayers, it offers high quality data for solar and wind project assessments and policy planning. The geoUmbriaSUIT QGIS plugin[91] performs sustainability assessment in a GIS environment using a multi-criteria algorithm based on environmental, economic and social criteria.

85 http://www.recharge-green.eu
86 http://cordis.europa.eu/project/rcn/64623_en.html
87 http://re.jrc.ec.europa.eu/pvgis/index.htm
88 http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#
89 http://cip-pakistan.geo-solutions.it/MapStore
90 http://irena.masdar.ac.ae
91 https://plugins.qgis.org/plugins/geoUmbriaSUIT

4.3 A new generation of integrated Earth system models to deepen our understanding of complex Earth systems and human dynamics across different disciplines, and to underpin systems-based policies and strategies for sustainable development

The efficient and timely creation of complex integrated Earth system models capable to analyze and simulate diverse conditions and changes will require the reuse of functionality already available in FOSS/FOSS4G software and the development of new ones. FOSS/FOSS4G is uniquely poised to make major contributions in this arena for two reasons. First, FOSS4G already offers a suit of sophisticated analytical capabilities, and second, because the source code is open and modular, developers can integrate FOSS4G, or extract and reuse some of their functionality to incorporate it into larger more complex analytical and simulation systems of both physical and human-environment interactions. For example, GRASS GIS has been extensively used for modeling the ecology of both plant and animal invasive species (e.g. Pitt et al. 2011; Neteler et al. 2011; and the GlobalChangeBiology project[92]). It has been also used to simulate and predict the long-term evolution of the Paneveggio forest (northern Italy) based on changes in human activities (Tattoni et al. 2011) and to correlate changes in the agro-forest landscape with the loss of traditional ecological knowledge (Ianni et al. 2015). GRASS GIS and R have been used to monitor the presence of primates in relation to human disturbances (Cavada et al. 2016). Designed around QGIS, the Water Observation and Information System (WOIS)[93] is a decision support tool that integrates processing and hydrological modelling for cost-effective management of water resources in Africa. A plugin[94] for gvSIG based on JGrassTools[95] performs modelling

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92 https://sites.google.com/site/globalchangebiology
93 http://qgis.org/en/site/about/case_studies/africa_tiger.html
94 http://outreach.gvsig.org/case-studies/gis-tools-water-supply-systems-implementation-using-jgrasstools-and-gvsig
95 https://github.com/moovida/jgrasstools

and simulation to optimize management of water supply systems, while SAGA is used for the spatial modelling of natural hazards in the Bavarian Alps (Kerkhof and Becht 2006). The Global Disaster Alert and Coordination System (GDACS)[96], jointly developed by the European Commission and the UN, combines Web-based geoprocessing using ZOO WPS and GRASS GIS to alert the international community in case of major sudden disasters. Finally, ZOO WPS was used to create DSS for rainfall modelling as part of a FOSS4G architecture to build a geoportal for North Vietnam (Brovelli et al. 2013b).

4.4 Science-based data, tools and resources to support improved resilience of people, communities and economies, including disaster risk reduction

The production of science-based data is increasing at an exponential rate. The processing of big amounts of data in a timely fashion is becoming a major challenge. To approach these types of issues Spatial Databases, such as PostGIS, are becoming an invaluable tool. In the United States at the National Renewable Energy Lab (NREL)[97] PostGIS is being used to process data in an effective and scalable manner to support the institution's mission (Getman 2015). SpatiaLite is also commonly used worldwide thanks to its simplicity, ease of use and flexibility. Apart from its well-known integration in other FOSS/FOSS4G projects (e.g. Debian, Fedora, GDAL, QGIS, R, Geopaparazzi and OpenStreetMap), SpatiaLite is currently used for FE-related needs by a large number of organizations such as the managers of the Yellowstone National Park and Idaho nature reserves, the Mozambique government, the World Health Organization (WHO) to monitor bird flu in the Southeast Asia, and the National Oceanic and Atmospheric Administration (NOAA) for oceanic studies. These applications were

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96 http://www.gdacs.org
97 http://www.nrel.gov

described by Alessandro Furieri, the creator of SpatiaLite, in a personal communication to the authors on February 19, 2016. An important application of Rasdaman is the storage of netCDF output files generated by the Global Flood Awareness System (GloFAS)[98], which uses a hydrological model to produce daily river flood forecasts at the global scale. Rasdaman is also at the core of the EU EarthServer project[99], which is building a platform for optimizing access to big data from Earth observation systems. Applications of MySQL Spatial include the Korean local governments management systems of their water supply network and hazardous material transportation. CouchDB is used in an online planning support system to predict fire behaviour (Choi et al. 2015). MongoDB is used in an application performing spatio-temporal visualization and analyses of telecommunication data flows in urban areas (Brovelli et al. in press).

The role of geodata catalogues is crucial to manage, describe, search and retrieve geospatial data. Applications of GeoNetwork (which integrates other FOSS4G tools like OpenLayers) have been deployed by diverse organizations such as the geocatalogues of the Food and Agriculture Organization (FAO)[100], the Netherlands Environmental Assessment Agency[101], the Australian Institute of Marine Science[102], the ISRIC – World Soil Information[103], the Netherlands Coordination Office of the UN Spatial Data Infrastructure (UNSDI)[104], and the geoportal of the Global Earth Observation System of Systems (GEOSS)[105]. A noteworthy implementation of pyCSW is the Platform for

98 http://www.globalfloods.eu
99 http://www.earthserver.eu
100 http://www.fao.org/geonetwork
101 http://geoservice.pbl.nl/geonetwork/srv/en/main.home
102 http://data.aims.gov.au/geonetwork/srv/eng/main.home
103 http://85.214.194.220/geonetwork/srv/en/main.home
104 http://www.geonetwork.nl
105 http://www.geoportal.org

Urban Management and Analysis (PUMA)[106] of the World Bank, focused on the study of urban and population expansion.

A significant example of a fully FOSS4G-based project to support the use and reuse of data is Publica Mundi[107]. It uses several FOSS4G here mentioned including Rasdaman, PostGIS, ZOO, GeoServer and OpenLayers to support the full life cycle of open geospatial data and enable the development of cross-boundary, demand-aware and scalable applications. ZOO WPS is also used together with other FOSS4G tools for the Osaka City University Disaster-risk Reduction Project (ODRP)[108], a WebGIS system based on OpenLayers to promote disaster risk awareness through community disaster prevention education. ZOO is used for computing on the Web both the risk factor of buildings and the routes to the nearest rescue shelter.

4.5 Scenarios for transformative development pathways that enable global sustainability, to help evaluate different strategies and options

This FE need requires the support of systems that can clearly and eloquently present information on current conditions, and illustrate scenarios in a compelling way that inspire people and institutions to change toward sustainable development alternatives. Both desktop and Web-based FOSS4G technologies can be used to run model simulations and evaluate/choose optimal alternatives for meeting sustainable development goals. GRASS GIS was used as early as the 1990's as a modeling and simulation platform in a DSS for hazardous waste management (Frysinger et al. 1993). A more recent example is the SITGAP DSS (Cannata and Antonovic 2015b) used by the Civil Protection Agency of Locarno and Vallemaggia (Switzerland). The system is based on an open source architecture that uses PostGIS, GeoServer, istSOS, pyWPS and

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106 http://puma.worldbank.org
107 http://www.publicamundi.eu
108 http://wps.media.osaka-cu.ac.jp/osaka

OpenLayers. The system integrates several information sources to perform hydrological modeling, provide meteorological forecasts and evaluate risk scenarios. Similarly, the above mentioned ENORASIS and IMRR projects perform natural resources management optimization using FOSS/FOSS4G software. The former implements the well-known Weather Research & Forecasting (WRF) open source model[109], while the latter is based on an open source stack including Drupal, istSOS, Geoserver, OpenLayers and Octave.

4.6 Critical contributions to key debates on global sustainability issues, including inputs to scientific assessments and decision-relevant syntheses

Robust and well-established FOSS4G (as well as private/proprietary/closed-source) applications in this field have yet to be developed. However, an interesting start in this direction is provided by the collaboration frameworks mentioned in Section 1. Among the notable implementations of GeoNode the following are worth mentioning. The Joint Research Center (JRC) of the European Commission, created an SDI to collect and disseminate results of geospatial analysis related to the assessment of the impact of the Syrian crisis[110]. The UN World Food Program (WFP), created a platform to enhance preparedness for humanitarian emergencies[111]. The US Department of State, created an application for publishing open geodata produced by government agencies to support decision-makers and partners during complex emergencies, natural disasters, and diplomatic activities worldwide[112]. GeoNode is also used in a collaboration platform created by the World Bank to share geospatial data for the development of Haiti[113], and as an integrated management platform for enhancing environmental monitoring and

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109 http://www.wrf-model.org
110 http://geonode.jrc.ec.europa.eu
111 http://geonode.wfp.org
112 http://geonode.state.gov
113 http://haitidata.org

inform decision-making in the Caribbean region[114]. An important open source

application built on top of GeoNode is GeoSHAPE (Geospatial capabilities for Security,

Humanitarian Assistance, Partner Engagement)[115], designed to enable geo-collaboration

between mission partners in coordinated and uncoordinated operations. The most

relevant application of PoliCrowd is on a platform for sustainable tourism in northern

Italy (Brovelli and Zamboni 2015).

4.7 Innovations in communicating, engaging and visualising global change and sustainability, fully exploiting the potential of new technologies and overcoming differential access to information across the world

FOSS/FOSS4G in this area can play an important role by facilitating access to cutting-

edge software and functionality and helping to reduce the digital divide that separates

developed from developing nations (James 2003). Also, the visualization capabilities

available in several FOSS4G such as in 2D and 3D Web clients (which often represent

the only visible part of the architecture depicted in Figure 1) enable the interactive

visualization of geospatial data stored in databases published through the Web.

Examples of 2D applications based on FOSS4G are the OSM (OpenStreetMap) Tasking

Manager[116] used by HOT (Humanitarian OpenStreetMap Team) to coordinate the

collaborative mapping in areas hit by natural disasters, and the forecast viewer[117] of the

GloFAS system mentioned above. The former makes use of Leaflet, while the latter uses

MapServer and OpenLayers for the display of data. MapServer and OpenLayers were

also used to create the popular Minnesota Department of Natural Resources[118] WebGIS

system. Coupled with GeoServer, OpenLayers is also used by FAO to display global

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114 http://c-read.net
115 http://geoshape.org
116 http://tasks.hotosm.org
117 http://www.globalfloods.eu/glofas-forecasting
118 http://www.dnr.state.mn.us/maps/compass.html

major fishing areas of tunas and billfishes[119] and aquatic species distribution[120]. PostGIS, GeoServer and OpenLayers are the foundation of the geoportal[121] for GlobeLand30, the first global land cover dataset at 30 meters resolution (Chen et al. 2014; Han et al. 2015). It is worth mentioning that the first accuracy assessment of this dataset at a national level was also performed using FOSS4G (Brovelli et al. 2015c). The map viewer of ESA Sentinels Scientific Data Hub[122], which provides distributed mirror archives and bulk dissemination capabilities for the EO Sentinels products, is based on OpenLayers also. It is worth mentioning that the geoportal of the Swiss Confederation[123], is also built using OpenLayers. It was recently awarded the "2015 eGovernment special prize" (Swiss Confederation 2015). Many applications of OpenLayers have been also described in the previous subsections. A system featuring OpenLayers and Leaflet viewers as well as several other FOSS4G solutions (PostGIS, MySQL, MapServer, GeoServer, deegree and GeoNetwork) is the Bolivia's SDI, named GeoBolivia[124].

Among 3D systems using open source Virtual Globes it is worth mentioning EOLi (Earth Observation Link), the European Space Agency's (ESA) client for Earth Observation Catalogue and Ordering Services[125], and a monitoring tool[126] developed by the US Federal Aviation Administration (FAA) providing meaningful visualizations of rich amounts of data at various scales. Both are based on World Wind (a Virtual Globe developed by NASA). World Wind is also embedded in the ESA SNAP (Sentinel

119 http://www.fao.org/figis/geoserver/tunaatlas
120 http://www.fao.org/figis/geoserver/factsheets/species.html
121 http://www.globallandcover.com
122 https://scihub.copernicus.eu/dhus/#/home
123 http://www.geo.admin.ch
124 http://geo.gob.bo
125 https://earth.esa.int/web/guest/eoli
126 http://worldwind.arc.nasa.gov/temp/faa/NESAT3DDemo.mp4

Application Platform) Desktop application[127], which allows to visualize and process Sentinel and other EO data, and in the Wildfire Management Tool (WMT)[128] which implements an advanced model to predict fire behaviour. Among Cesium's applications related to FE themes it is worth mentioning the 3D Harvesting Planter[129], a decision making environment for forestry management, and the mobile Web app WAVE (Waterway information for Vessels)[130], providing emergency information to fishermen in Louisiana. Finally, the energyglobe application[131] exploits WebGL Earth virtual globe for visualizing global energy patterns over time.

      Also worth mentioning are systems that incorporate physical models with 2D and 3D such as the Tangible Landscape system[132]. This system is a collaborative modelling environment for analysis of terrain changes. It combines a scanner, projector and a physical 3D model with GRASS GIS to analyse the impact of terrain changes by capturing the changes on the physical model, bringing them into the GIS, performing desired analysis or simulation and projecting the results back on the model in real-time (Petrasova et al. 2015).

5. Conclusions and recommendations

The reasons for FOSS/FOSS4G adoption vary from pragmatic to ideological, but they should be based not only on their technical merit, their no-cost feature, or their access to the source code. Adopting FOSS/FOSS4G for the wrong reasons can have unintended consequences, while not adopting them might leave considerable opportunities and benefits unused (Moreno-Sanchez 2012). FOSS4G software should be evaluated at par

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127 http://step.esa.int/main/download
128 http://www.emxsys.com
129 https://cesiumjs.org/demos/3DHarvestingPlanner.html
130 https://cesiumjs.org/demos/WAVE.html
131 http://energyglobe.paperplane.io
132 https://geospatial.ncsu.edu/osgeorel/tangible-landscape.html

with their private/proprietary/closed-source counterparts to select the solution that best addresses the context and informational needs where they will be used to develop the components, systems, and functionality that will be part of DE and FE. FOSS4G capabilities, range of applications, and user/developer/education communities have been growing and maturing rapidly around the world. Today there are more implementation experiences, educational resources, personnel know-how, commercial support services, and larger more experienced user/developer communities. These developments, among others, are reducing the impact of inhibitors that in the past have impacted the uptake of FOSS/FOSS4G solutions.

Because of their purpose and ultimate goals, DE and FE will be developed and maintained around the world following a philosophy of openness, sharing, and distributed-collaborative development. Technologies like FOSS/FOSS4G that align with this philosophy by being open, breaking barriers, facilitating access, and fostering the creation of communities of interest will play an important role in realizing the DE and FE visions. This paper has shown that there are already many stable implementations of FOSS4G solutions in high-level organizations working on large, sophisticated, mission-critical operations. These examples demonstrate the robustness, reliability and suitability of FOSS4G for contributing to achieve the FE vision and goals. Thanks to their modularity, openness, and extensibility, FOSS4G solutions are positioned to contribute to the realization of DE and FE visions. FOSS4G and its user/developer/education communities are clearly ready and capable to contribute to the FE endeavor, no doubt one of the most critical of the 21st century.

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