Singapore Journal of Tropical Geography

doi:10.1111/sjtg.12210

Free satellite imagery and digital elevation model analyses enabling natural resource management in the developing world: Case studies from Eastern Indonesia

Rohan Peter Fisher,[1] Sarah Elizabeth Hobgen,[1] Kristianus Haleberek,[2] Nelson Sula[3] and Iradaf Mandaya[4]

[1]Research Institute for Environment and Livelihoods, Charles Darwin University, Darwin, Australia
[2]Indonesian Forestry Department, Kupang District, Nusa Tenggara Timur, Indonesia
[3]Indonesian Health Department, Timor Tengah Selatan District Soe, Nusa Tenggara Timur, Indonesia
[4]Lembaga Pengembangan Masyarakat Pesisir dan Pedalaman (Lepmil) Kendari, Nusa Tenggara Timur, Indonesia

Correspondence: Rohan Fisher (email: rohan.fisher@cdu.edu.au)

Decentralization of governance and natural resource management is an ongoing process in many parts of Africa and Asia. Natural resource management requires spatial land resource data for planning. However, currently the financial and human capacity for natural resource mapping, monitoring and modelling remains low in local governments. In this context, this paper explores how new opportunities provided by the increasing availability of free satellite imagery, digital elevation data and open source spatial analysis software, can be applied by local government and NGOs to conduct sophisticated natural resource mapping and modelling in ways that meet their needs and incorporates local knowledge. Reported are cases of a local government using free geospatial data and GIS software to improve evidence-based natural resource management in the developing world with a focus on raster data applications for satellite image analysis and terrain modelling. It is argued that, through removing barriers to uptake, such applications provide a means of decentralizing landscape analysis skills to improve local natural resource management. This hypothesis is supported through examples of a local government applying these tools in eastern Indonesia, and within this context barriers to wider adoption are explored.

Keywords: GIS, remote sensing, DEM, decentralization, capacity building, open source

Accepted: 6 April 2017

Introduction

Policies aimed at government decentralization have been widely implemented throughout Latin America, Africa and Asia (Larson, 2002) with the goal of increasing efficiency, participation, equity, and accountability. With respect to natural resource management, decentralization aims to allow more proactive management which is sensitive to local needs leading to improved environmental sustainability (World Bank, 1988; Tacconi, 2007). Reviews of this approach have identified the capacity of local governing organizations as the primary factor limiting effective management (Larson, 2002; Oyono, 2004; Hartter & Ryan 2010; Arellano-Yanguas, 2011; Ribot *et al*., 2010; Blomquist *et al*., 2010). External advisors with minimal local knowledge to contextualize the advice they provide are commonly used to bridge the gap between limited capacity and the aspiration for good local governance. This lack of regional engagement with technical planning processes can result in a limited local understanding of planning outputs, leading to poorly informed and inappropriate management recommendations. These factors can result in reticence from local government to implement governance recommendations presented.

Information communication technology is often promoted as a tool for improving the evidence base and equity of governance in developing countries (Bertot *et al.*, 2010; OECD, 2005). However, it is also criticized for being deployed top-down thus failing to address the needs of local governments and communities (Heeks, 2010; Huang 2013). Geographic information technologies in particular have been criticized for preferentially empowering a techno-elite and disenfranchising local interests (Dunn *et al.*, 1997). It is argued that as maps give authority to particular conceptions of land value through defining a range of social and biophysical parameters, differential access to the technology, skills and data required to make them reinforces social and political inequity (Fox *et al.*, 2008).

To address the potentially disempowering aspects of mainstream GIS, mapping techniques have evolved to enhance local participatory planning processes and collaborative decision making (Rambaldi *et al.*, 2006; Elwood, 2011; McCall & Dunn, 2012). Many of these participatory GIS approaches have focused on low-tech methods for spatially enabling communities. There is also increasing interest in the potential for decentralized use of emerging low cost digital spatial tools and data for improving governance (Fisher & Myers, 2011). Over the last ten years there has been a rapid increase in the availability of free geospatial data and software (Moreno-Sanchez, 2012). It has been argued that free GIS software, when coupled with free spatial data, is providing new opportunities for enhanced transparency and increased community engagement in environmental management (Baker and Williamson, 2006; Fuller, 2006; Fisher, 2012). Building local capacity for evidence-based governance can facilitate the incorporation of local context and potentially lead to more informed planning decisions.

Geospatial applications for land resource mapping, monitoring and modelling provide key data underpinning Natural Resources Management planning (NRM). The current generation of Free and Open Source (FOS) geospatial software and free data has removed the need for licensing and data purchase, which was a significant barrier to broader involvement in land resource mapping, monitoring and modelling for local governments. Advances in computing hardware have enabled use of sophisticated spatial analytical tools on standard laptops. Furthermore the increasing availability of free satellite imagery, elevation data and raster based spatial analysis software is providing new opportunities for community stakeholders to combine the quantitative analysis of 'hard' data with qualitative local knowledge (Fuller, 2006; Spiegel *et al.*, 2012).

McCall and Dunne (2012) determined five criteria to evaluate contribution of participatory GIS (PGIS) to good governance:

1. strengthening legitimacy through participation;
2. creating respect for and legitimising local knowledge;
3. developing equity within communities and between communities and governments;
4. demonstrating competence; and
5. creating accountability.

This paper explores the evolving potential for 'hi-tech' raster analysis tools to converge with the aspirations of participatory GIS for increasing local capacity and improved governance in the developing world.

In summary, the centralized analysis of satellite image and elevation data to support local planning often results in outputs being misinterpreted by the producers; not fully understood by the consumers and not addressing locally relevant concerns. In this context, this paper explores the hypothesis that, through removing barriers to uptake, Free Open Source (FOS) GIS software and free data provide a means of decentralizing landscape analysis skills to improve local natural resource management. To investigate this, case studies in Eastern Indonesia are presented to demonstrate the application of raster based spatial analysis tools by local government and NGOs. The potential for contribution to improved natural resources management in each of the case studies are assessed using the criteria for participatory mapping to contribute to good governance following McCall and Dunne (2012). Case studies focus on the use of satellite imagery for mapping and monitoring and the application of digital elevation models for topographic and hydrological modelling.

Natural resource management in eastern Indonesia

Indonesia moved towards decentralized governance in 1999 through the Regional Autonomy program which has devolved power to over 400 local government districts (*Kabupaten*). These districts are now responsible for managing a range of essential services including health, education, infrastructure and environment (Holtzappel & Ramstedt, 2009; Fitrani *et al.*, 2005). While management responsibilities have been given, technical capacity remains low, and districts are largely reliant on remote 'experts' (central government or consultants) for the provision of planning and technical information.

This lack of capacity is of particular concern in eastern Indonesia which suffers from slow economic development and high rates of poverty due largely to:

1. harsh climatic conditions;
2. inadequate infrastructure;
3. poor access to markets (Booth, 2004).

As a result, most of eastern Indonesia is classified as 'underdeveloped' by the central government (Kementerian DPDTT, 2015). In addition, low local revenue has led to a reliance on central government funding to support development activities. This means a degree of planning power has been transferred back to the central government where decisions are made about what and how development projects are funded. A lack of accurate, reliable, current local data and analysis skills reduces the ability of local governments to participate in the planning process and negotiate funding and planning arrangements. This is a significant issue in eastern Indonesia where the seasonally arid and remote conditions are markedly different from western Indonesia and pose development problems poorly understood by 'experts' from the wet, fertile and densely populated western regions.

In eastern Indonesia three key problems have been observed particularly with regards to natural resource mapping:

1. data provided to districts according to needs perceived by central government does not always meet the actual local needs;
2. mapping is provided only in image format, often at a scale too coarse for practical planning; and
3. the source data, analysis methods and levels of accuracy for derived data products are rarely provided.

The following case studies demonstrate the potential for the local government and NGOs to undertake their own analysis to solve problems they have identified, using FOS geospatial applications and free data.

Study area

The case studies described are from the eastern Indonesian provinces of East Nusa Tenggara (NTT) and South East Sulawesi (see Figure 1). The districts of NTT province are some of the driest in Indonesia, with a short wet season (3 – 5 months), variable and relatively low mean annual rainfall. Food security is an increasing challenge with a growing population highly dependent on agriculture, and greater variability in rainfall projected under climate change scenarios. South East Sulawesi, whilst less poor than NTT, is similarly remote with minimal infrastructure and low levels of decentralized capacity. However, South East Sulawesi is rich in mineral and forest resources that leave it open to exploitation by external forces without effective local oversight.

Methods

Examples of analysis of free data using open source software are presented as case studies to demonstrate the applicability in a development context and provide practical examples of the potential contributions to good governance. All the examples presented in this paper have been developed following joint capacity building activities between local government, NGO's and universities in eastern Indonesia and northern Australia. Capacity building activities included training in use of FOS GIS software and their application in collaborative research projects over several years. Importantly the training was contextualized to local issues and delivered locally.

Whilst there are a number of sophisticated free open source raster analysis packages available, including GRASS, White Box and ILWIS (Steiniger & Bocher, 2009; Neteler *et al.*, 2012), SAGA GIS (Conrad *et al.*, 2015) was chosen as the focus of training because it:

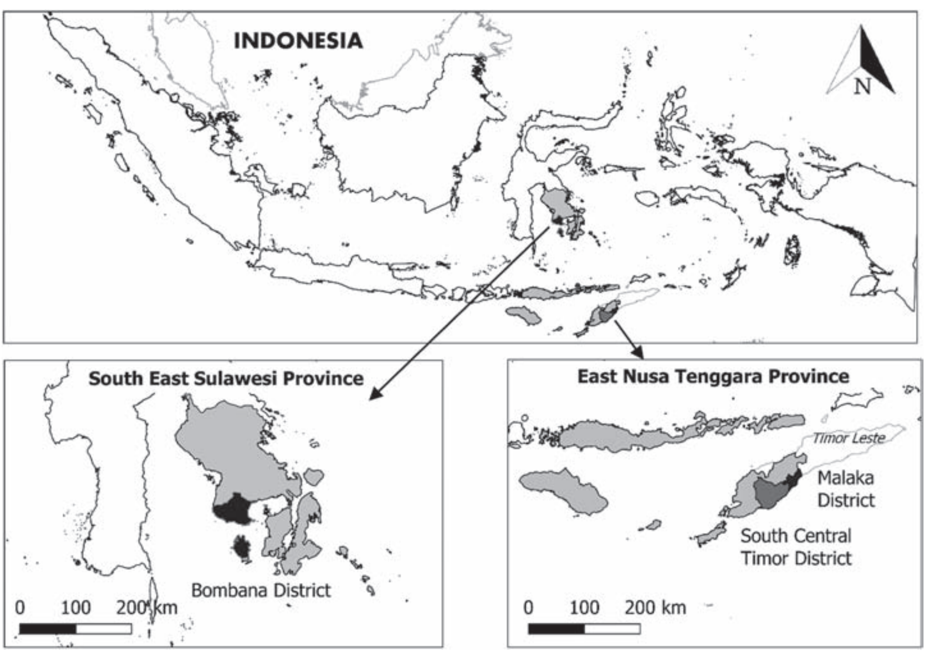

Figure 1. *Case study locations in Bombana, Malaka and South Central Timor Districts, eastern Indonesia.* *Source*: Map prepared by Sarah Hobgen. Data from http://www.gadm.org/country

1. provides the easiest, onestep process for Landsat data visualization;
2. has a simple, onestep process for sophisticated hydrological and terrain modelling;
3. is a compact package that does not require installation and therefore easy to share;
4. has an easy to comprehend interface similar to other GIS packages;
5. works seamlessly with all standard GIS data formats; and
6. has an active development team responsive to user suggestions for processing tools and bug fixes.

It should be noted, that although examples presented here use one software tool, the broad processing functionality described is common to the others mentioned above and is becoming increasingly common in other traditionally vector focused software (i.e. QGIS, MapWindow). All case study applications described here were independently initiated and analysed by the Indonesian government and NGO authors of this paper. In some cases technical advice and mentoring was provided by the remaining authors.

Data sources

The primary base data used for the described applications were all free and easily accessible via the internet i.e. Landsat 8 for current land cover mapping (libra. developmentseed.org), Landsat 5 (earthexplorer.usgs.gov) for historic mapping, Shuttle Radar Topographic Mission 1 sec (SRTM) digital evaluation data (earthexplorer. usgs.gov) and the Worldclim modelled rainfall data (www.worldclim.org) (Table 1).

For each of the case studies the broader NRM issue, local context, methods, and GIS outputs are briefly described as well as new knowledge arising from the work. In addition, the case studies are assessed with regard to McCall and Dunn's (2012) evaluation criteria.

Case study 1: Modelling impacts from small scale mining

Artisanal and Small Scale Mining (ASM) provides income for an estimated 30 million people worldwide. The contribution of ASM to the global mineral and metal production markets is also substantial, estimated at 15 – 20 per cent of global production (Buxton, 2013). ASM is generally defined as mining performed by communities with little financial capital and without government recognition, often on small or marginal deposits (Eftimie *et al.*, 2012; Buxton, 2013). Over the last 10 years, mineral prices have risen sharply causing a rapid increase in the number of people involved in ASM. Despite the growing number of people and resources involved in ASM, this form of mining is often viewed negatively by international agencies and governments, due to the potential environmental and health effects associated with unregulated mining. ASM does however provide underprivileged people with direct access to the mineral wealth of their land, alternative income streams, improved food security and development of community resilience. Formalization and regulation of ASM is one option for governments and communities

Table 1. Free to download data sets used in NRM modelling case studies.

Application	Landsat 8	Landsat 5	SRTM	Worldclim	Other
ASM Impact	x		x		
Fire Mapping	x	x			
Erosion Potential	x		x	x	x
Disaster Risk	x	x	x		x

Source: Prepared by Rohan Fisher.

to minimize the negative impacts and maximize the benefits of ASM. Effective governance and regulation of mining requires capacity in mapping and monitoring of ASM to enable understanding of the potential downstream sediment and contaminant flows of mining. This is critical for assessing and managing the potential environmental and public health impacts.

Context

Artisanal gold mining began in the South East Sulawesi district of Bombana with a 'rush' in late 2008. From September 2008 until April 2009, official records show that more than 63,000 people flooded into the district from neighbouring areas and beyond the province (Zulkarnain, 2010). Environmental damage has been widespread with increased erosion and river sedimentation from river bank and alluvial mining; the conversion of forest land and markedly reduced downstream river flows and water quality. Particular concerns involve the long term health impacts from the use of mercury in processing the gold.

Method

In this case study, two key spatial analyses were undertaken by staff from a local NGO to help understand the impact of the small-scale gold mining in Bombana. These analyses were:

1. mapping of the current land cover to determine the distribution and extent of mining in relation to surrounding land use;
2. sediment flow modelling to show the extent of potential off-site mining impacts.

The land cover mapping was conducted by analysing Landsat 8 imagery using an Object Based Image Analysis technique to segment the satellite image into regions of similar spectral statistical classes. Using SAGA, the image was segmented and grouped into spectral class polygons. These polygons were then manually assigned broad spectral land cover classes by visual image interpretation based on field experience. Finally, the polygons were reclassified into cover sub-classes based on their spatial context and pattern. For example, the spectral forest class was divided into forest and mangroves based on proximity to the ocean and estuarine waterways. The flow path modelling was conducted using SRTM DEM data using the flow path module. This analysis was conducted using the Multiple Flow Direction algorithm (Freeman, 1991) and used the mine site classification to define the sediment source grid cells.

GIS outputs

The land cover mapping showed that 16km^2 of land had been affected by gold mining. Based on this, subsequent sediment flow modelling suggests that 23 km^2 of rice fields and 27 km^2 of aquaculture in the estuarine mangroves could be impacted by the mining residue, including mercury and cyanide contamination (see Figure 2). In addition, whilst mining had occurred in a relatively discrete area, the flow path modelling showed that mining was impacting two catchments with outflow points separated by over 70 km of coastline.

Contribution to good governance

The landscape modelling tools available in SAGA enabled local government and NGO's to develop a better understanding of the impacts of this activity in a whole catchment context, and provided evidence to advocate for supporting policies and resource

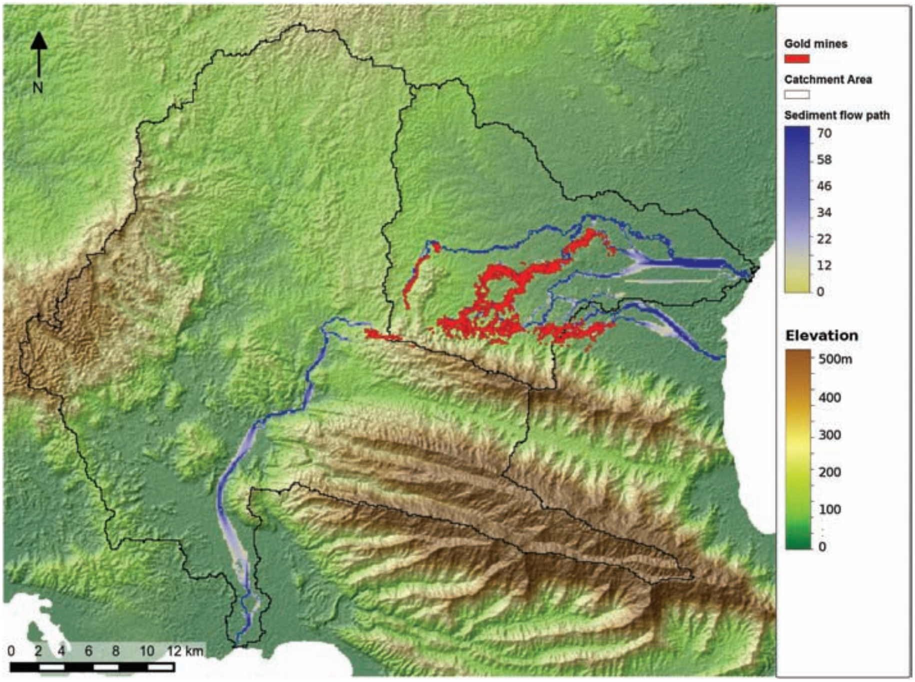

Figure 2. *Maps of land cover and sediment flows produced by local NGO officer using FOS geospatial approach.*
Source: **Map prepared by Iradaf Mandaya. Analysis by author using Landsat 8 and SRTM 90 m DEM data.**

allocation to tackle this issue. The modelled flow of potentially toxic sediments through rice fields and into an extensive aquaculture region, clearly showed off site impacts in need of consideration. In addition, the modelling showed the mining sediment flowing through two separate catchments with outflow points distant from one another, potentially affecting two unrelated communities. Only one of these catchments was previously considered as impacted. This mapping increased the legitimacy of concerns around public health from mercury use in artisanal gold mining and was used to guide subsequent environmental mercury concentration sampling and testing. The ability to produce such mapping and modelling at a local level and its potential for ongoing monitoring of artisanal and larger mining activities is helping to create accountability for these operations in the future.

Case study 2: Catchment function analysis

Integrated catchment management is a focus of Indonesian natural resource planning, with recent legislation requiring all major catchments to produce a management plan as a matter of urgency (RI, 2012). One of the primary aims of catchment management is to reduce river sediment loads and therefore reduce sedimentation of irrigation and domestic water supplies. This study, conducted by a local government forestry officer, aimed to develop a better understanding of the biophysical processes affecting the largest catchment in west Timor through developing base line erosion risk and fire frequency data sets. The research was conducted in the Benenain catchment (3300 km^2), which supports the livelihoods of over one million people. It has significant environmental degradation issues, impacting downstream on intensive irrigated agriculture development.

Erosion and sediment source mapping

Sedimentation of irrigation infrastructure causes water shortages in many irrigation areas in NTT (Hobgen *et al.*, 2014). Understanding the source of sediments within a catchment can be a useful guide for management planning. Use of the Revised Universal Soil Loss Equation (RUSLE) is currently prescribed in Indonesian catchment management planning regulations for calculating soil erosion loss (Wischmeier & Smith, 1978). Whilst the validity of the RUSLE method for calculating soil loss in whole catchments has been questioned (Zhang *et al.*, 1996; Evans, 2012), particularly in the wet-dry tropics (Brooks *et al.*, 2014), it has been shown to be useful for assessing relative erosion risk within a catchment for targeting erosion remediation and reforestation projects (Witz & Muga, 2009). Planning and agriculture agencies could also apply the results of RUSLE as locations with high to severe erosion risk are also likely to be unsuitable for cultivated agriculture.

Method. Following methods modified from Hobgen *et al.*, (2014), free climate modelling (Worldclim), satellite imagery (Landsat 8) and elevation (SRTM) datasets were used to produce rainfall intensity (R), land cover (C) and slope/length (LS) factors. Soil (K) and Land Use (P) factors were derived from national mapping data sets. These datasets were combined using the RUSLE equation (R * K * LS * C * P) (Wischmeier & Smith, 1978). The processing steps to derive each factor are shown in Figure 3.

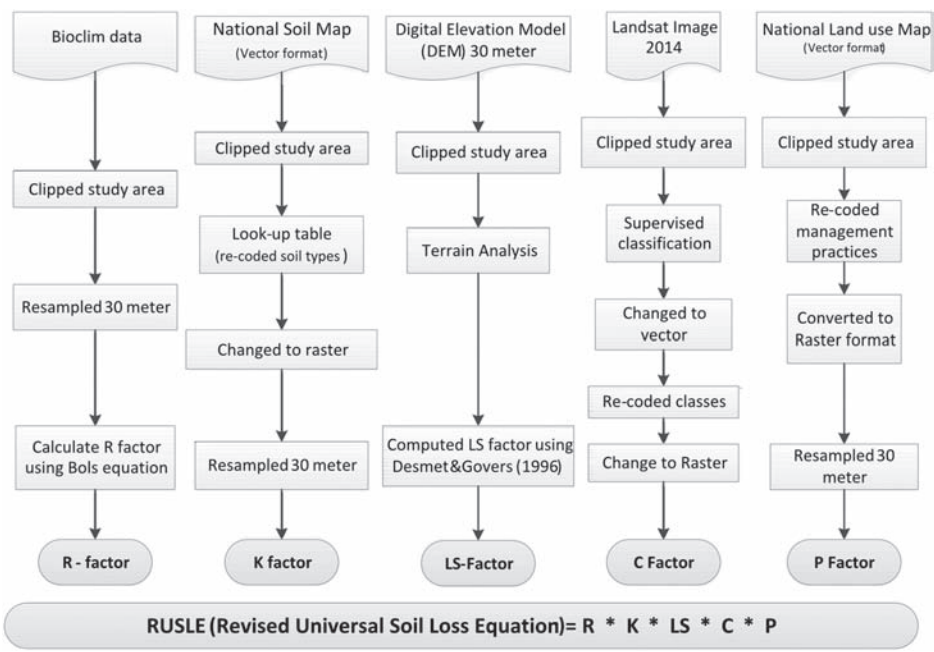

Figure 3. *Summary of the free open source software and free data approach to calculate the Revised Universal Soil Loss Equation*.
Source: Kristianus Haleberek.

GIS results. The RUSLE mapping indicated that 15 per cent of the catchment has a high potential erosion risk. The 'high' RUSLE class, whilst occuring throughout the catchment, was predominantly located in the upper reaches of the tributaries (Figure 4).

Contribution to good governance. Recent studies in the wet-dry tropics have demonstrated a 10 − 1000 fold overestimation of soil loss due to rill and sheet erosion (Brooks *et al*., 2014). The regulated methods rely on dated secondary data with analysis undertaken by external and remote consultants producing misleading soil loss metrics (KemHut, 2011). The most significant immediate outcome from the application of RUSLE in this study was the development of a clear understanding of the parameters and processes used in the calculation. The officer conducting this study developed new skills that enabled an understanding of the output and development of strategic validation plans. Developing local capacity to conduct RUSLE analysis facilitates a better understanding of both the inaccuracy of the estimates of erosion volume and, despite these inaccuracies, the utility of such analysis for assessment of relative erosion risk. This understanding thus builds accountability into externally produced erosion data and promotes equity in the analysis of such data. Importantly, targeted on-ground validation also enhances local understanding of erosion processes and the means to mitigate them.

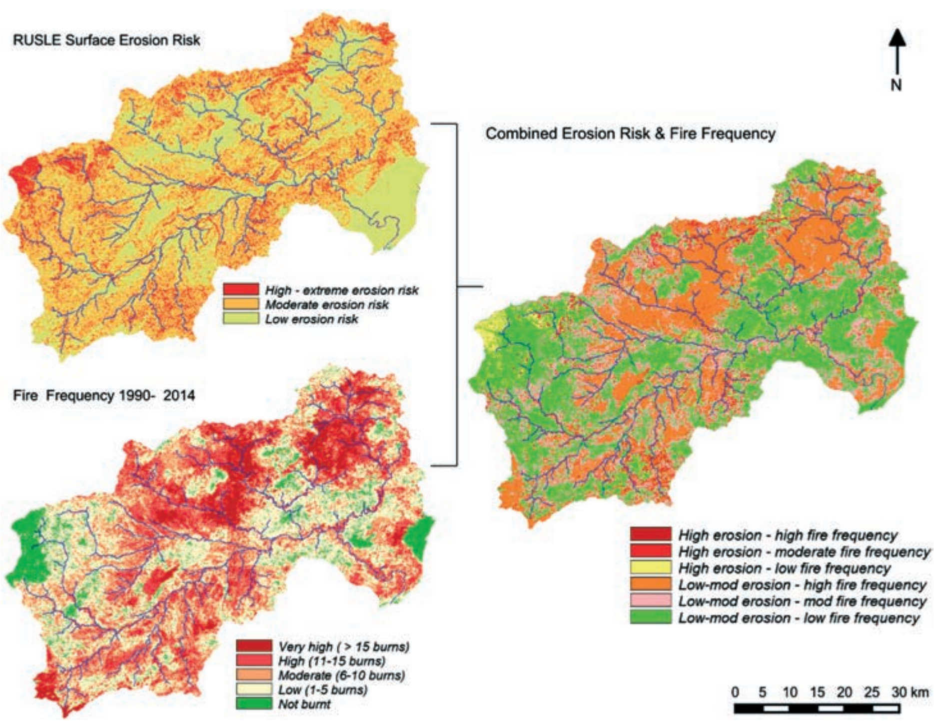

Figure 4. *RUSLE relative erosion risk mapping, fire frequency mapping and a combined erosion risk and fire frequency map for the Benenain catchment in West Timor.*
Source: Map prepared by Kristianus Haleberek. Analysis of Landsat 5 and 8 and SRTM data.

Seasonal fire mapping

Uncontrolled fire remains one of the largest natural resource management challenges in the dry savanna landscapes of NTT. High frequency and intense savanna fires are widely understood by local people to have negative environmental and economic impacts as they damage pasture and agro-forestry plantations.

Current official fire management agendas in Indonesia are strongly focused on forest fires of western Indonesia (Yong & Peh, 2014) with little acknowledgment or research on the savanna fires of the drier eastern regions (Russell-Smith *et al.*, 2000). Collecting baseline data to understand the extent and frequency of fire is essential for any fire management program. Although seasonal fire extent mapping using classification of Landsat imagery has previously been implemented, using proprietary software in a number of eastern Indonesian locations (Fisher *et al.*, 2006), it is yet to be undertaken routinely.

Method. The land cover mapping was conducted using Landsat 8 and 5 imagery clipped to the catchment boundary over a 15 year period, between 1990 and 2014. An Object Based Image Analysis technique was used to segment the satellite image into regions with similar spectral classes using red, infrared and thermal bands. After the initial segmentation, the polygon classes representing fire were manually selected. Polygons misclassified as fire were then manually deleted. The edited fire classification was then converted into raster grids and combined to produce fire frequency maps.

GIS results. The fire mapping showed that, on average, 39 per cent of the catchment or around 1280 km^2 was burnt each year. In addition the analysis showed that 34 per cent was burnt more than 10 times over the 15 year period (Figure 4).

Contribution to good governance. Prior to this study no fine scale baseline data existed showing the extent, distribution and frequency of fire in West Timor. The lack of knowledge about fire in this region is further compounded by coarse global fire products that fail to map smaller fires thus effectively hiding significant landscape issues (Laris, 2005). Whilst fire is perceived in West Timor as a significant human-ecological phenomenon, the large proportion burnt (up to 62 per cent in 2014), shown by this mapping was far in excess of that generally recognized. The fire mapping work presented in this study produced by a local analyst provides an authoritative counter to current popular and official conceptions that underestimate the role of fire in these landscapes. In doing so it strengthens legitimacy of local NRM concerns and in turn enhances respect for local knowledge. This mapping is now being used to initiate planning discussions amongst land managers in this catchment creating accountability and transparency in decision making. Competence was demonstrated through applying simple and repeatable techniques that will facilitate ongoing fire monitoring programs.

New knowledge — Combined RUSLE and fire frequency mapping

This analysis revealed a spatial patterning generated from two independent datasets indicating that 24km^2 of the landscape with high erosion potential has also been characterized by high fire frequency in recent years (see Figure 4). Given the primary erosion control measure promoted by the government is reforestation, identification of fire as a risk factor affecting both surface soil erosion and the success of reforestation projects is leading to investigations of ways to improve fire management processes. Fire mapping is thus an important baseline dataset informing further field investigation into the causes and impacts of fire in this catchment.

Case study 3: forest cover change mapping

Reforestation projects are undertaken by district forestry departments annually. Forest cover change mapping was undertaken by the district planning agency in South Central Timor (West Timor) to determine changes in forest cover over time, with the aim of evaluating the effectiveness of past reforestation projects and to assist in assessing current reforestation project proposals.

Method

Forest cover change analysis was undertaken using unsupervised classification of Landsat 5 and Landsat 8 imagery in SAGA GIS of 3 images from 1993, 2010 and 2013. Classified classes were allocated as 'forest' or 'not forest' from visual analysis of imagery combined with local knowledge. Imagery from the late dry season was selected to minimize classification, as forests remain green during the dry season while grasslands are dormant.

In areas where the greatest forest cover change occurred, field inspections and informal interviews with local farmers were used to test the validity of the data and to determine the cause of forest cover change.

GIS results

Initial results suggest that forest cover increased overall during the period 1993-2010, then decreased during the subsequent period 2010 – 2013 (see Figure 5), despite official reports that reforestation projects had been successfully implemented and had resulted in an increase in forest cover over this period. Interviews with local farmers confirmed the loss of forest cover due to timber harvesting for house building and for sale.

Contribution to good governance

Large investments have been made into forestry and reforestation projects across Indonesia with both commercial and environmental protection goals. However, there

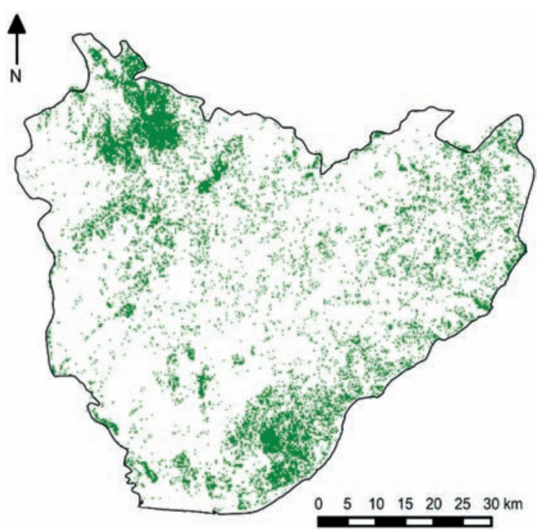

Figure 5. *Forest cover in the South Central Timor District mapped by a local government officer using free open source software to analyse free satellite imagery.*
Source: Map prepared by Nelson Sula. Analysis of Landsat 8 data.

is rarely systematic monitoring of the outcomes of these projects (Nawir & Rumboko, 2008). In this case, forest cover change mapping was undertaken by the local government planning agency, whose role is to assess and provide funding for all locally funded projects, including reforestation. The finding that forest cover was in fact decreasing motivated the planning agency to seek further understanding of possible causes of deforestation in specific locations, in order to better understand the issues, creating accountability and transparency for assessing outcomes of these forestry projects. In addition, the incorporation of local knowledge into the assessment and interpretation of the results is strengthening legitimacy and building respect for local knowledge. As a result of this work the planning agency intends to continue Landsat based monitoring to determine appropriate locations for, and evaluate the effectiveness of, reforestation projects. Such objective regular monitoring by local agencies is relatively easily implemented using Landsat producing accurate and meaningfully interpreted data.

Discussion

Whilst open source methods for fire mapping (Teodoro & Duarte, 2013), land cover mapping (Steiniger & Hay, 2009) and erosion analysis (Hobgen *et al.*, 2014) have previously been described, these studies have largely focused on non-local or centralized research studies rather than for planning purposes. In contrast, the case studies described in this paper demonstrate the utility of applying free and open source GIS and free spatial data in a decentralized development context. The potential contribution of these case studies to support improved natural resource governance suggest some general principles are assessed more broadly against McCall and Dunne's (2012) criteria as follows:

1. *Strengthening legitimacy* – The legitimacy of spatial data is strengthened by decentralized production through two primary mechanisms:
   a. the selection of appropriate data for spatial analysis at useful scales to provide levels required to meet specific local planning needs; and
   b. the application of local knowledge for interpreting analysis outputs leading to clearer identification of errors or inconsistencies.

   This community participation in the production process leads to a sense of ownership and better understanding of the strengths and weaknesses of outputs. This in turn can enable more appropriate and effective use of the spatial data as a planning tool. Whilst local agencies may not have the same financial or human resources for conducting some specialized forms of spatial or hydrological analyses, in many situations local applications are likely to produce more useful and affordable planning data.
2. *Creating respect for local knowledge* — Whilst remote sensing and terrain modelling applications do not directly incorporate indigenous and local knowledge, local government agencies are more likely to incorporate regional understanding of the landscape into their analyses. This allows for spatial data to be placed in a historic, social and environmental contexts and thus incorporate significant cultural and political influences on land use planning.
3. *Developing equity* — Raster based modelling and analysis, when used as a tool for creating more accurate, locally owned data, can assist in redressing the power imbalance between central government authorities and local agencies. It adds authority and legitimacy to their understanding of the environment and NRM concerns, and builds skills and confidence, enabling critical evaluation of data and planning recommendations generated by external assessments. This was highlighted as a significant outcome by all the government participants engaged in the work.

4. *Demonstrating competence* — Approaches using FOS software for analysis of free data enable local government staff to produce and manage their own data, in accordance with their needs. Data can easily be updated using the same methods to provide comparable data sets and interrogated in different ways for emerging requirements.
5. *Creating accountability* — Locally created and owned maps can contribute to increased transparency in decision making processes by building skills to allow lower level agencies to critically assess programs and outcomes. Where the use of external agencies and restricted or expensive data is required, an understanding of the basic principles and techniques of remote sensing and GIS can enable local government to conduct a more informed assessment of the accuracy and utility of mapping provided and to ensure that consultants are obliged to provide data in a GIS format.

In addition to the governance benefits described above, there are a range of technical advantages to choosing FOS GIS software. In contrast to commercial packages, open source software are consistently more secure, reliable, and adaptable (Casson & Ryan, 2006; Krogh & Hippel 2006; Holck *et al.*, 2005; Hwang, 2005). The open-source community-led development model, in which a diverse community of developers and users work together for the longer-term benefit of an application, builds more robust, targeted and responsive applications. Developer communities generally produce more regular updates fixing bugs, improving stability and maintaining relevance. Open source software also allows easy customisation to fit specific application contexts and cross platform interoperability.

FOS GIS software shares many of these advantages (Steiniger & Hay, 2009). SAGA-GIS, for example, was developed primarily as a platform to support ongoing geospatial research and development. SAGA is developed by users for users and is constantly updated by developers and the user community, keeping it relevant with cutting edge geospatial research. Currently SAGA offers more than 700 geo-scientific modules responding to scientific questions and needs (Conrad *et al.*, 2015). This flexibility and responsiveness allows FOS GIS software to quickly and seamlessly incorporate tailor made functionality to facilitate specific processes or to address particular NRM issues. This development model has resulted in FOS GIS platforms not only at the cutting edge of science, but which are simultaneously simple to install and apply in remote, resource poor contexts. Indeed from a donor or development program perspective, the cost benefit of supporting FOS applications, where an application or plugin once built is freely available to all, has considerable global and long term benefits.

Much of the developing world's GIS work is currently conducted using pirated copies of commercial software. In Indonesia for example, many universities and government agencies rely on unlicensed commercial GIS software. The decision to use commercial software is based on the false assumption that it is better than the open source alternatives, even though 'cracked' GIS applications are difficult to install, often unstable and have limited access to software updates. It also follows, due to the ubiquity of unlicensed GIS in many developing countries, development programs not promoting FOS GIS software are implicitly supporting the continued use of illegal software. To overcome this, FOS GIS software should be promoted as a legitimate tool in both local government and universities. Significantly Indonesia's national mapping authority (Badan Informasi Geospatial) has acknowledged the potential contribution of FOS GIS software through implementing the National Law (RI, 2011) that actively supports FOS geospatial use. Whilst an important step, this law, due to a lack of an integrated program to support and legitimize FOS use, so far seems to have had minimal impact on the culture of GIS teaching and use in Indonesia.

Despite the obvious benefits of open source software, three of the most commonly cited drawbacks are that it is has:

1. under-developed user interface;
2. poor user support; and
3. limited documentation and training material (Steiniger & Bocher, 2009).

Firstly in contrast with some open source software, the user interfaces of most FOS GIS software packages are comparable to their commercial counterparts. For SAGA-GIS the deployment of many spatial operations is easier than for many other packages after the basic format logic is learnt.

Secondly, user support for open source software is largely provided by the developer team and supported by the user community. Consequently, as the number of users increases, so does the support base. The large increase in the number of users for FOS GIS software worldwide (Steiniger & Bocher, 2009) has improved access to support through user forums in many different languages. Developers of open source software also often rely on user feedback via forums for improvements, thus they are responsive to user questions. Local language forums have also been developed using social media as a fast and effective tool for communicating with other local users.

Finally, one significant remaining barrier for implementation of FOS GIS software and free data approaches is a lack of clear, comprehensive training material. In order to support decentralized application, training material needs to be produced that:

1. utilizes free data;
2. is contextualized to local NRM issues;
3. results in data that meet local needs and central government reporting requirements; and
4. is produced in appropriate languages.

Conclusion

It is clear from the case studies presented in this paper that the emerging range of free raster based spatial analysis tools and data can contribute to improved natural resource management in a decentralized developing world context. The assessment presented suggests that active advocacy and ongoing support for the use of FOS GIS capacity could:

1. build legitimacy in the outputs through participation;
2. support equity, competence and accountability by developing skills;
3. contribute to a common global resource pool of training material;
4. legitimise the use of FOS GIS tools; and
5. help build a larger legal geospatial industry in the developing world.

Considering these potential benefits, it could be argued that all rural development and NRM programs creating new spatial data in less developed countries should include support for FOS GIS applications, collaborative mapping and monitoring.

Whilst more work needs to be done to demonstrate long term impacts, this paper has demonstrated potential benefits of investing in training materials distributed in an open access format and on ground capacity building. This enables local government agencies to perform their own mapping and monitoring to improve governance of natural resources. Support for software and training material development and the wider adoption of these tools requires advocacy from funding organisations involved in natural resource management projects.

Acknowledgements

The authors would like to thank Dr Bronwyn Myers, Dr Jeremy Russel-Smith and Professor Stephen Garnett for their helpful suggestions and Michael and Lorraine Hobgen for comprehensive English editing.

References

Arellano-Yanguas, J (2011) Aggravating the resource curse: Decentralization, mining and conflict in Peru. *The Journal of Development Studies* **47** (4), 617–38.

Baker JC, Williamson RA (2006) Satellite imagery activism: sharpening the focus on tropical deforestation. *Singapore Journal of Tropical Geography* **27** (1), 414.

Blomquist W, Dinar A, Kemper KE (2010). A framework for institutional analysis of decentralization reforms in natural resource management. *Society and Natural Resources* **23** (7), 620–35.

Booth A (2004) Africa in Asia? The Development Challenges Facing Eastern Indonesia and East Timor. *Oxford Development Studies* **32** (1), 19–35.

Brooks AP, Spencer JR, Borombovits D, Pietsch T, Olley J (2014) Measured hillslope erosion rates in the wet-dry tropics of Cape York, northern Australia: Part 2, RUSLE-based modeling significantly over-predicts hillslope sediment production. *Catena* **122**, 117.

Bertot J, Jaeger P, Grimes J (2010) Using ICTs to create a culture of transparency: E-government and social media as openness and anti-corruption tools for societies. *Government Information Quarterly* **27** (3), 264–71.

Buxton A (2013) *Responding to the challenge of artisanal and small-scale mining: How can knowledge networks help? Sustainable Markets Paper*. International Institute for Environment and Development, London.

Casson T, Ryan P (2006) Open standards, open source adoption in the public sector, and their relationship to Microsoft's market dominance. In Bolin S (ed) *Standards Edge: Unifier or Divider*, 87–99. Sheridan Books, Hunt Valley, MD.

Conrad O, Bechtel B, Bock M *et al*. (2015) System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. *Geoscientific Model Development Discussions* **8** (2), 2271–312.

Dunn CE, Atkins PJ, Townsend JG (1997) GIS for development: a contradiction in terms? *Area* **29**, 151–9.

Eftimie A, Heller K, Strongman J, Hinton J, Lahiri-Dutt K, Mutemeri N (2012) *Gender Dimensions of Artisanal and Small-Scale Mining: A Rapid Assessment Toolkit*. World Bank, Washington DC.

Elwood S (2011) Participatory approaches in GIS and society research: Foundations, practices, and future directions. In Nyerges T, Couclelis H, McMaster R (eds) *The SAGE Handbook of GIS and Society*, 381–99. SAGE, UK.

Evans R (2012) Assessment and monitoring of accelerated water erosion of cultivated land — when will reality be acknowledged? *Soil Use and Management* **29** (1), 105–18.

Fisher R (2012) Tropical forest monitoring, combining satellite and social data, to inform management and livelihood implications: Case studies from Indonesian West Timor. *International Journal of Applied Earth Observation and Geoinformation* **16**, 77–84.

Fisher R, Bobanuba WE, Rawambaku A, Hill GJ, Russell-Smith J (2006) Remote sensing of fire regimes in semi-arid Nusa Tenggara Timur, eastern Indonesia: current patterns, future prospects. *International Journal of Wildland Fire* **15** (3), 307–17.

Fisher RP, Myers BA (2011) Free and simple GIS as appropriate for health mapping in a low resource setting: a case study in eastern Indonesia. *International Journal of Health Geographics* **10** (11). https://doi.org/10.1186/1476-072X-10-15.

Fitrani F, Hofman B, Kaiser K (2005) Unity in diversity? The creation of new local governments in a decentralising Indonesia. *Bulletin of Indonesian Economics* **41** (1), 57–79.

Fox J, Suryanata K, Hershock P, Pramono AH (2008) Mapping boundaries, shifting power: The socio-ethical dimensions of participatory mapping. In Goodman M, Boykoff M, Evered K (eds) *Contentious geographies: environmental knowledge, meaning, scale,* 203–17. MPG Books Ltd, Bodmin, Cornwall.

Freeman GT (1991) Calculating catchment area with divergent flow based on a regular grid *Computers and Geosciences* **17**, 413–22.

Fuller DO (2006) Tropical forest monitoring and remote sensing: A new era of transparency in forest governance? *Singapore Journal of Tropical Geography* **27** (1), 15–29.

Hartter J, Ryan SJ (2010) Top-down or bottom-up? : Decentralization, natural resource management, and usufruct rights in the forests and wetlands of western Uganda. *Land Use Policy* **27** (3), 815–26.

Heeks R (2010) Do information and communication technologies (ICTs) contribute to development? *Journal of International Development* **22** (5), 625–40.

Hobgen SE, Myers BA, Fisher RP, Wasson RJ (2014) Creating a Sediment Budget in a Data Poor Context: An Example from Eastern Indonesia. *Geografiska Annaler: Series A, Physical Geography* **96** (4), 513–30.

Holck J, Larsen MH, Pedersen MK (2005) Managerial and Technical Barriers to the Adoption of Open Source Software. In Franch X, Port D (eds) *COTS-Based Software Systems. ICCBSS 2005. Lecture Notes in Computer Science*, vol **3412**. Springer, Berlin, Heidelberg.

Holtzappel CJ, Ramstedt M (2009) *Decentralization and regional autonomy in Indonesia: implementation and challenges*. Institute of Southeast Asian Studies, Singapore.

Huang YE (2013) The Future's Fix: Using Information and Communications Technology to Reduce Global Poverty. Available at: http://hdl.handle.net/11021/24185 (accessed 13 November 2016).

Hwang S (2005) Adopting open source and open standards in the public Sector: five deciding factors behind the movement. *Michigan Journal of Public Affairs* **2**, 119.

KemHut (2011) Peraturan Rehabilitasi Hutan dan Lahan No 76/2008 [Regulations for Rehabilitation of Forest and Lands No.76/2008]. Ministry of Forestry, Jakarta

Kementerian Desa Pembangunan Daerah Tertinggal dan Transmigrasi (2015) *Presidential Decree No 131/2015 Determination of disadvantaged Districts for 2015–2019 Medium Term Planning*. Available at: http://www.hukumonline.com/pusatdata/detail/lt57a44f87a4973/node/lt512d993c981c2/perpres-no-131-tahun-2015-penetapan-daerah-tertinggal-tahun-2015-2019 (accessed 13 July 2017).

Krogh G Von, Hippel E Von (2006) The promise of research on open source software. *Management Science* **52** (7), 975–83.

Laris PS (2005) Spatiotemporal problems with detecting and mapping mosaic fire regimes with coarse-resolution satellite data in savanna environments. *Remote Sensing of Environment* **99** (4), 412–24.

Larson AM (2002) Natural Resources and Decentralization in Nicaragua: Are Local Governments Up to the Job? *World Development* **30** (1), 17–31.

McCall MK, Dunn CE (2012) Geo-information tools for participatory spatial planning: Fulfilling the criteria for 'good' governance? *Geoforum* **43** (1), 81–94.

Moreno-Sanchez R (2012) Free and Open Source Software for Geospatial Applications (FOSS4G): A mature alternative in the geospatial technologies arena. *Transactions in GIS* **16** (2), 81–8.

Neteler M, Bowman MH, Landa M, Metz M (2012) GRASS GIS: A multi-purpose open source GIS. *Environmental Modelling & Software* **31**, 124–30.

Nawir A, Rumboko L (2008) *Rehabilitasi hutan di Indonesia: Akan kemanakah arahnya setelah lebih dari tiga dasawarsa?* [Forest rehabilitation in Indonesia: Where to after more than three decades?] Center for International Forestry Research (CIFOR), Bogor, Indonesia.

OECD (2005) ICTs for Development: Financing Activities of DAC Members. *OECD Papers* **5** (1), 141.

Oyono PR (2004) One step forward, two steps back? Paradoxes of natural resources management decentralisation in Cameroon. *The Journal of Modern African Studies* **42** (01), 91–111.

Rambaldi G, Kyem PAK, McCall M, Weiner D (2006) Participatory spatial information management and communication in developing countries. *The Electronic Journal of Information Systems in Developing Countries* 25-1.

RI (2012) *Peraturan Pemerintah tentang Pengelolaan Daerah Aliran Sungai PP37/2012* [Government Regulation about River Catchment Management]. President of Republic of Indonesia, Jakarta.

RI (2011) *Undang-undang Republik Indonesia Nomor UU4/2011 tentang Informasi Geospasial*. P. o. [Indonesian Law No 4 Year 2011 about Geospatial Information] Republic of Indonesia, Jakarta.

Ribot, JC, Lund JL, Treue T (2010) Democratic decentralization in sub-Saharan Africa: its contribution to forest management, livelihoods, and enfranchisement. *Environmental Conservation* **37** (1), 35–44.

Russell-Smith J, Hill G, Djoeroemana S, Myers B (2000) Fire and sustainable agricultural and forestry development in Eastern Indonesia and Northern Australia. *Proceedings of an international workshop held at Northern Territory University, Darwin, Australia, 13–15 April 1999*. Australian Centre for International Agricultural Research (ACIAR).

Spiegel SJ, Ribeiro CA, Sousa R, Veiga MM (2012) Mapping spaces of environmental dispute: GIS, mining, and surveillance in the Amazon. *Annals of the Association of American Geographers* **102** (2), 320–49.

Steiniger S, Bocher E (2009) An overview on current free and open source desktop GIS developments. *International Journal of Geographical Information Science* **23** (1), 1345–70.

Steiniger S, Hay GJ (2009) Free and open source geographic information tools for landscape ecology. *Ecological Informatics* **4** (4), 183–95.

Tacconi L (2007) Decentralization, forests and livelihoods: Theory and narrative. *Global Environmental Change*, **17** (3-4), 338–48.

Teodoro AC, Duarte L (2013) Forest fire risk maps: a GIS open source application–a case study in Norwest of Portugal. *International Journal of Geographical Information Science* **27** (4), 699–720.

Wischmeier WH, Smith DD (1978) *Predicting rainfall erosion losses : a guide to conservation planning*. US Department of Agriculture, Science and Education Administration, Washington DC.

Witz T, Muga E (2009) GIS-based Rapid Risk Assessment of erosion potential in the Aesesa catchment, Nage Keo — Ngada Flores, NTT Indonesia. In Fisher R, Myers B, Sanam M, Tarus V (eds) *GIS Applications for sustainable development and good governance in Eastern Indonesia and Timor Leste*. Charles Darwin University Press, Darwin.

World Bank (1988) *World Development Report 1988*. Washington DC, World Bank Group. Available at: http://documents.worldbank.org/curated/en/620641468165566752/World-development-report-1988 [accessed 13/7/2017].

Yong, DL, Peh KS-H (2014) South-east Asia's forest fires: blazing the policy trail. *Oryx, The International Journal of Conservation,* 16.

Zhang L, O'Neill AL, Lacey S (1996) Modelling approaches to the prediction of soil erosion in catchments. *Environmental Software* **11**, 123–33.

Zulkarnain, I (2010) *Strategi Pengembangan Wilayah Pertambangan* [Strategy for development of Mining Areas], 72. Lembaga Ilmu Pengetahuan Indonesia, Jakarta.