Catena 149 (2017) 770–781

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Assessment of the impacts of clear-cutting on soil loss by water erosion in Italian forests: First comprehensive monitoring and modelling approach

P. Borrelli [a,*], P. Panagos [a], M. Märker [b,c], S. Modugno [d], B. Schütt [e]

[a] European Commission, Joint Research Centre, Institute for Environment and Sustainability, Via E. Fermi 2749, I-21027 Ispra, VA, Italy
[b] Department of Agronomy and Land Management, University of Florence, Piazzale delle Cascine 14, I-50144 Florence, Italy
[c] Heidelberg Academy of Sciences and Humanities, University of Tübingen, Rümelinstr. 19–23, 72070 Tübingen, Germany
[d] University of Cassino and Southern Lazio, Department of Human Sciences, Social and Health, Cassino, Italy
[e] Department of Earth Sciences, Physical Geography, Freie Universität Berlin, Malteserstraβe 74–100, Haus H, 12249 Berlin, Germany

ARTICLE INFO

Article history:
Received 12 July 2015
Received in revised form 16 February 2016
Accepted 22 February 2016
Available online 4 March 2016

Keywords:
Forest monitoring
Landscape sensitivity
Accelerated soil erosion
Soil protection
Policy making
Italy

ABSTRACT

As a member of the European Union, Italy has committed to the maintenance and protection of its forests based on sustainable forest development and management practices. According to Eurostat, Italy has the seventh largest forest surface available for wood supply in the EU-28, which is equal to 8.086 million hectares. For 2012, the Italian National Institute of Statistics estimated the total roundwood production of Italy to be 7.7 million m^3, from a harvested forest surface of 61,038 ha. Large parts of the country's forests, mainly located in vulnerable mountainous landscapes that are highly sensitive to environmental changes, are subject to anthropogenic disturbance driven by wood supply interests. Despite the extensive logging activities and the well-known impacts that such management practices have on the soil-related forest ecosystems, there is a lack of spatially and temporally explicit information about the removal of trees. Hence, this study aims to: i) assess the soil loss by water erosion in Italian forest areas, ii) map forest harvests and iii) evaluate the effects of logging activities in terms of soil loss by means of comprehensive remote sensing and GIS modelling techniques. The study area covers about 785.6×10^4 ha, which corresponds to the main forest units of the CORINE land cover 2006 database (i.e. broad-leaved forests, coniferous forests and mixed forests). Annual forest logging activities were mapped using Landsat imagery. Validation procedures were applied. A revised version of the Universal Soil Loss Equation (USLE) was used to predict the soil loss potential due to rill and inter-rill processes. To ensure a thorough modelling approach, the input parameters were calculated using the original methods reported in the USDA handbooks. The derived high-resolution data regarding forest cover change shows that 317,535 ha (4.04% of the total forest area in Italy) were harvested during the period under review. The predicted long-term annual average soil loss rate was 0.54 Mg ha^{-1} yr^{-1}. The average rate of soil loss in forests that remained undisturbed during the modelled period is equal to 0.33 Mg ha^{-1} yr^{-1}. Notably, about half of the soil loss (45.3%) was predicted for the logged areas, even though these cover only about 10.6% of the Italian forests. The identified erosion hotspots may represent a serious threat for the soil-related forest ecosystems, and are in contrast to the EC Thematic Strategy for Soil Protection and Water Framework Directive.

1. Introduction

The topic of land degradation due to soil loss by water erosion has been extensively studied in Italy. Several soil erosion test sites (Zanchi, 1988; Vacca et al., 2000; Bagarello and Ferro, 2010, among others) and numerous publications focus on different soil erosion phenomena (e.g. Marker et al., 2007; Borselli et al., 2008; Della Seta et al., 2009; Torri et al., 2013). It is surprising that little attention has been paid to the soil degradation and erosion processes in forests. Academic research on soil loss by water erosion in Italian forest areas is almost exclusively limited to a few studies carried out by the Italian National Research Council (CNR) based on experimental sites in southern Italy (Iovino and Puglisi, 1991; Sorriso-Valvo et al., 1995; Porto et al., 2009; Porto et al., 2014) and some monitoring and modelling exercises (Garfì et al., 2006; Borrelli et al., 2013a; Borrelli and Schütt, 2014). In fact, there is only a vague understanding of the soil erosion processes, their magnitude and their impact on Italian forests.

The international scientific literature reports that forests are generally unaffected by intense erosion processes (Swanston, 1991). For 18 undisturbed forested watersheds of the USA, Patrick (1976) found soil loss rates of between 0.02 and 0.04 Mg ha^{-1} y^{-1}. Reviewing plot measurements in Europe, Cerdan et al. (2006) found an average soil loss rate

* Corresponding author.
E-mail addresses: pasquale.borrelli@jrc.ec.europa.eu, lino.borrelli@yahoo.it (P. Borrelli).

http://dx.doi.org/10.1016/j.catena.2016.02.017

due to sheet and rill erosion of 0.15 Mg ha^{-1} y^{-1}. Despite these significant findings for undisturbed forests, it is important to recognise that the low susceptibility of forest lands to erosion and the small amount of sediment loss from forest soils dramatically change as soon as the area undergoes forestry activities (Swanston and Swanson, 1976; Stott et al., 2001). Increased soil loss rates associated with forest harvesting were found in several areas of the world, in particular (but not limited to) the US, the UK, Japan, New Zealand and Southeast Asia (Swanston and Swanson, 1976; Derose et al., 1993; Greer et al., 1996; Kitahara et al., 2000; Stott et al., 2001). For Italy, Borrelli and Schütt (2014) measured an average soil loss rate of 49 Mg ha^{-1} y^{-1} during the twelve months following a tree harvesting event in the Central Apennines. In the disturbed mountainous areas of Calabria in the Southern Apennines, high soil loss rates ranging from 100 to 150 Mg ha^{-1} y^{-1} were observed during an experimental investigation by the CNR (Sorriso-Valvo et al., 1995).

Human-accelerated soil loss rates in forests can cause a large number of on-site effects (Williams, 2003; Morgan, 2005) that significantly influence the soil-related functions such as carbon storage, biodiversity as well as human needs for recreation (Van Oost et al., 2005a; Ojea et al., 2012; Gamfeldt et al., 2013; Wall et al., 2013). Increased rates of soil loss from hillslopes also induce a series of off-site impacts as a result of increased bedload transport (Roberts and Church, 1986). Sediments transported downstream disturb the ecology of the river network (Marks and Rutt, 1997) and cause siltation problems in artificial lakes and reservoirs (Romero-Díaz et al., 2007), which in turn affects the drinking-water supply and the effectiveness of the hydroelectric plants (Della Seta et al., 2009).

Eurostat (2013) reports that 66.4% of the Italian forest land (i.e. forest and other wooded land) is privately owned, and about 42% of the forest surface is managed as coppice forest (INFC, 2007). The Italian National Institute of Statistics (Istat, 2015) reports that about 61,038 ha of coppice forests were harvested in Italy during the year 2012 to meet the timber demand (Istat, 2014). A significant area of Italian forests, mostly located in vulnerable mountainous landscapes that are highly sensitive to environmental changes (Borrelli et al., 2013b), is subject to anthropogenic disturbance driven by wood supply interests (Borrelli et al., 2014a).

As a member of the European Union, Italy has committed to the maintenance and protection of its forest lands in order to ensure sustainable forest development and management (MCPFE, 1993). Despite the extensive logging activities and their significant risks of accelerating soil erosion processes, current scientific research lacks spatially and temporally explicit information about these tree harvesting activities and their impacts on the soil-related forest ecosystem. Therefore, this study aims to assess the soil loss by water erosion from Italian forests, and to evaluate the effects of logging operations in terms of soil loss using various modelling techniques. As a first step, annual forest logging activities were carefully mapped by means of remote sensing and Geographic Information System (GIS) operations. A revised version of the Universal Soil Loss Equation (USLE) (Renard et al., 1997) was used to predict the soil loss rates due to rill and inter-rill processes. To ensure a sound modelling approach, the input parameters were calculated based on the original methods reported in the USDA handbooks (Wischmeier and Smith, 1978; Renard et al., 1997) and spatially described by means of advanced special interpolation techniques.

2. Study area

Italy is located in southern Europe, between latitudes 35° and 47° North and longitudes 6° and 19° East (Fig. 1). About 35% of the territory is covered by forests ($1046.75 \cdot 10^4$ ha) (INCF, 2005). The study area covers about $785.6 \cdot 10^4$ ha, which corresponds to the main forest units described within the CORINE land cover 2006 database (EEA, 2014), i.e. broad-leaved forests ($547.9 \cdot 10^4$ ha, 70%), coniferous forests ($128.6 \cdot 10^4$ ha, 17%) and mixed forests ($109.1 \cdot 10^4$ ha, 13%). These units include a mosaic of natural and semi-natural forest ecosystems that are characterised by different climates, biogeographical conditions and pedo-geological diversity (APAT, 2005; INFC, 2005). The dominating tree species are *Quercus* (*petraea*, *robur*, *petraea*, *cerris*, *carpinifolia*, *sativa*, *ilex*) *Fagus sylvatica*, *Picea abies* and *Abies alba* (Vacchiano et al., 2012). The coefficient of woodiness (forest area/land area) (INFC, 2005) is lower in the southern regions (the EU NUTS-2 administrative units of Apulia (ITF4), Basilicata (ITF5), Calabria (ITF6)) and on the islands (Sicily (ITG2) and Sardinia (ITG1)) (Table 1). Here, other forms of wooded land (e.g. shrubs and macchia) make up a substantial part of the forest area. The most densely wooded regions are Liguria and Trentino, with a coverage rate of 69.7% and 65.5%, respectively.

3. Material and methods

3.1. Approach overview

The spatio-temporal pattern of rill and inter-rill soil erosion processes in Italian forest lands is based on a spatially distributed modelling approach (Fig. 2). Prior to the soil erosion modelling phase, the status of the vegetation and the logged areas were outlined by remote sensing and GIS operations. As a first step, the impact of a 30-year period of forest logging was established based on forest change detection techniques (2002–2011) and a rules-based approach that randomly generated clear-cut areas (1982–2001). As the second step, the long-term soil loss rates (Mg ha^{-1} y^{-1}) were predicted by means of a revised version of the Universal Soil Loss Equation (USLE).

3.2. Forest monitoring

3.2.1. Mapping of coppice forest clear-cut areas

Cloud-free Landsat satellite imagery composed of 406 selected images was downloaded via the Global Visualization Viewer (Glovis, 2014) from the Earth Resources Observation and the Science Center (EROS) of the United States Geological Survey (USGS). The imagery allowed for optimal study area coverage over a 10-year time period (2002–2011) using 175 Landsat Thematic Mapper (TM) and 231 Landsat Enhanced Thematic Mapper Plus (ETM+) images.

For Italy, the EROS Landsat images are geometrically adjusted (L1T standard) to remove any systematic geometric errors related to the sensor (USGS, 2011). All of these images were pre-processed, including image resampling (Williams, 2006), dark object subtraction and radiometric normalisation (Chavez and Mackinnon, 1994) to improve the accuracy of the procedure of forest change detection (Hansen et al., 2008; Potapov et al., 2008). A forest/non-forest mask was generated using the CORINE shapefiles of broad-leaved forests (3.11), coniferous forests (3.12) and mixed forests (3.13). Subsequently, the forest areas were carefully examined by means of an image differencing technique (Singh, 1989) to detect the clear-cuts that were made between June 2002 and August 2011. More specifically, the method subtracts the spatially registered Normalized Difference Vegetation Index values (Jensen, 1986) of two images using a pixel-by-pixel procedure (Borrelli et al., 2013c). As a result of these operations, the forest logging areas were spatially and temporally defined in a set of ten annual shapefiles using Envi 4.7 and ArcGIS 10 (Borrelli et al., 2014a for more details). The final outcome, i.e. the representation of all clear-cut areas larger than 0.45 ha, went through a rigorous validation and rectification procedure based on multi-scale onscreen visual interpretation (i.e., 1:20,000, 1:10,000, and 1:5000) (Borrelli et al., 2014a).

3.2.2. Accuracy assessment of the clear-cut areas

The accuracy of the detected forest clear-cut areas rested on a confusion matrix based on a per-pixel analysis (Aronoff, 1982) to check the geometric accuracy, and a linear correlation analysis that manipulated the shapefile in a GIS environment for thematic accuracy. A set of clear-cut areas provided by an independent research group (Chirici et al.,