Catena xxx (2016) xxx–xxx

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 xxxx

*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 $785.6 \times 10^4$ 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
0341-8162/

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.,

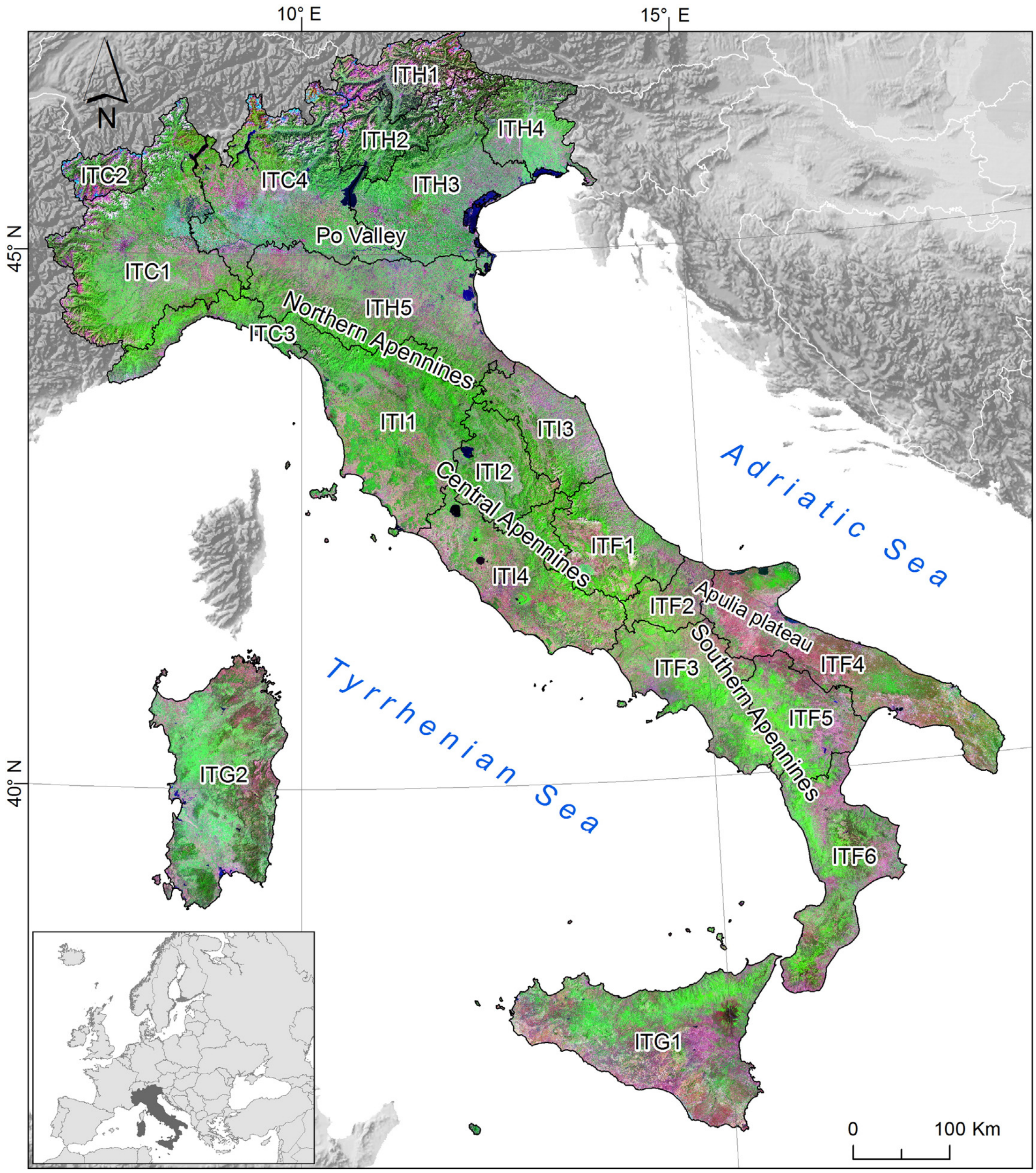


**Fig. 1.** Study area. Background image: Landsat TM mosaic false colour composite of the bands 7, 4 and 2.

2011) was used as reference data, while the clear-cut areas resulting from the monitoring activities of this study represented the classified data.

### 3.2.3. Clear-cuts simulation for the pre-monitoring period

The forest change related to timber harvesting during the decade from 2002 to 2011 was carefully mapped. Acquisition inconsistencies (EROS database) of Landsat images in Italy for the period prior to 2001 hampered the temporary extension of this mapping activity. To pursue the objective of this study, namely the prediction of the long-term soil loss by water erosion (Dissmeyer and Foster, 1984) and the forest logging activities in Italian forest lands, an additional dataset of clear-cut areas was simulated for the period between 1982 and 2001. This dataset was randomly generated based on the following assumptions: (i) the decrease in the annual timber harvest rate in Italy between 1980 and 2000 (−2% per year, Fabbio, 2010; Istat, 2014), (ii) the forest harvesting density and the characteristics of the clear-cut areas observed in the period 2002–2011 and (iii) a defined set of rules (Table 2).

A forest change density map was created to spatially describe the dynamics of the clear-cuts and to highlight the forest sectors that were mainly affected. The map was based on the Kernel Density algorithm (Silverman, 1986) that is included in the Spatial Analyst toolbox of ArcGIS 10.2 (ESRI). To enable this, the shapefiles were converted from polygons to points (creating centroid points of 30 × 30 m of clear-cut area).

### 3.2.4. Post-harvest vegetation development

Borrelli et al. (2013a) proposed that the post-harvest vegetation development in soil erosion modelling should be expressed as a time sequence in order to provide a USLE C factor which represents realistic vegetation conditions. Filed observations in central (Borrelli and Schütt, 2014) and southern Italy (Garfì et al., 2006) suggested that the harvested vegetation regains the coverage function of a moderately dense forest four years after the clear-cut. Trend analyses of Landsat Normalized Difference Vegetation Index (NDVI) and MODIS EVI vegetation indices (VIs) were performed to observe the properties of the

**Table 1**
Italian forestland statistics by NUTS-2 2013 administrative units (INFC, 2007).

| NUTS-2 | | Forest | Other wooded lands | Total forest coverage |
|---|---|---|---|---|
| ID | Name | | [ha] | |
| ITC1 | Piedmont | 870,594 | 69,522 | 940,116 |
| ITC2 | Valle d'Aosta | 98,439 | 7489 | 105,928 |
| ITC4 | Lombardy | 606,045 | 59,657 | 665,703 |
| ITH1 | South Tyrol | 336,689 | 35,485 | 372,174 |
| ITH2 | Trentino | 375,402 | 32,129 | 407,531 |
| ITH3 | Veneto | 397,889 | 48,967 | 446,856 |
| ITH4 | Friuli V.G. | 323,832 | 33,392 | 357,224 |
| ITC3 | Liguria | 339,107 | 36,027 | 375,134 |
| ITH5 | Emilia Romagna | 563,263 | 45,555 | 608,818 |
| ITI1 | Tuscany | 1,015,728 | 135,811 | 1,151,539 |
| ITI2 | Umbria | 371,574 | 18,681 | 390,255 |
| ITI3 | Marche | 291,394 | 16,682 | 308,076 |
| ITI4 | Lazio | 543,884 | 61,974 | 605,859 |
| ITF1 | Abruzzi | 391,492 | 47,099 | 438,590 |
| ITF2 | Molise | 132,562 | 16,079 | 148,641 |
| ITF3 | Campania | 384,395 | 60,879 | 445,274 |
| ITF4 | Apulia | 145,889 | 33,151 | 179,040 |
| ITF5 | Basilicata | 263,098 | 93,329 | 356,426 |
| ITF6 | Calabria | 468,151 | 144,781 | 612,931 |
| ITG1 | Sicily | 256,303 | 81,868 | 338,171 |
| ITG2 | Sardinia | 583,472 | 629,778 | 1,213,250 |
| | National coverage | 8,759,200 | 1,708,333 | 10,467,533 |

**Table 2**
Set of rules defined to simulate the long-term clear-cut potential of an area.

| Rule | Description |
|---|---|
| i) | Random clear-cut areas were generated solely inside the forest area under investigation (Corine land cover 2006 database. Units: Broad-leaved forests, coniferous forests and mixed forests) |
| ii) | Buffer areas were generated around the mapped clear-cut areas to avoid overlapping with the simulated ones. |
| iii) | The size of the random clear-cut areas was set to 3 ha (consistent with the average of the mapped clear-cut areas). |
| iv) | The simulation area was subset to follow the topographical characteristics (i.e., elevation range and slope) observed on the mapped clear-cut areas. |
| v) | An overlap of clear-cut areas was no permitted. |

forest, the disturbances and the post-disturbance recovery processes in order to verify whether or not the post-harvest vegetation development and the USLE C factor assessed in the local observations were representative of the general national conditions.

Two independent satellite imagery time-series covering the period from 2002 to 2011 were created: i) ten years of 16-days combined MODIS Enhanced Vegetation Index (EVI, Huete et al., 2002) (MODIS — Moderate Resolution Imaging Spectroradiometer Terra) and ii) ten growing season Landsat ET/ETM+ NDVI. The centroids of the polygon shapefiles which represented the wood harvests during 2005 were generated (corresponding to the midterm of our time-series). Subsequently, the values of the vegetation indices (VIs) were imported into the attribute table of each centroid. The centroids with information gaps, for instance due to cloud disturbances or Landsat 7 Scan Line Corrector-Off malfunctions, were removed. To minimise the effect of mixed pixels resulting from a 'mixture' of the two land uses (forest and harvesting area), the centroids underwent further filtering procedures. Finally, two sets of centroids were employed (MODIS n = 510; Landsat n = 250) for the trend analysis in order to consider the different spatial resolutions of the sensors (pixel area: MODIS 6.5 ha; Landsat 0.09 ha).

### *3.3. Soil erosion modelling — Conceptual schema of the USLE model*

The evaluation of the long-term average soil loss by water erosion in the Italian forests was carried out using a modified version of the USLE model (Dissmeyer and Foster, 1984) in a GIS environment. USLE belongs to the class of detachment-limited models. Accordingly, the flow can theoretically transport an infinite quantity of sediment, but the amount of sediment actually available to be transported is limited by the soil detachment capacity, which is represented by the rainfall erosivity factor of the model. The soil loss in terms of tonnes per hectare and year due to inter-rill and rill erosion processes is calculated according to Wischmeier and Smith (1978), based on the following multiplicative equation:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (1)$$

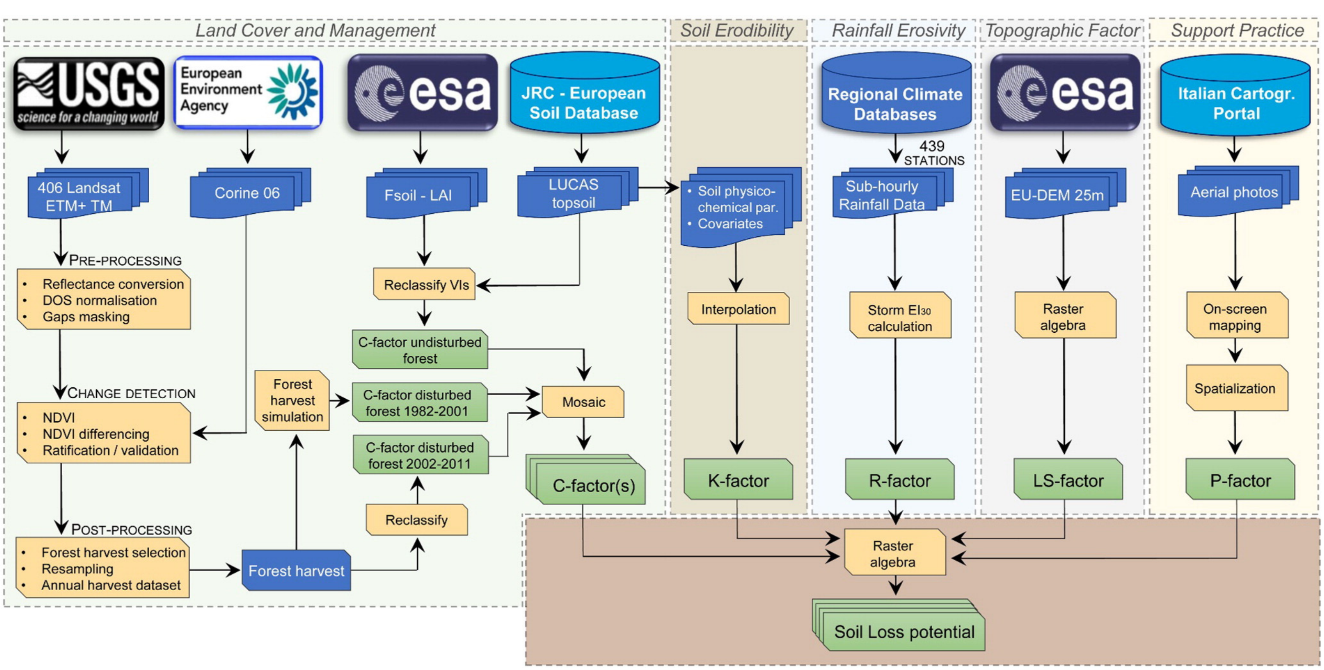


**Fig. 2.** Workflow — Assessment of vegetation cover, tree harvesting and soil loss potential for the Italian forestland.

where: A [ Mg $ha^{-1}$ $yr^{-1}$] is the long-term average soil loss rate, R [MJ mm $h^{-1}$ $ha^{-1}$ $yr^{-1}$] is the rainfall erosivity factor, K [Mg h $MJ^{-1}$ $mm^{-1}$] is the soil erodibility factor, L [dimensionless] is the slope length factor, S [dimensionless] is the slope steepness factor, C [dimensionless] is the land cover and management factor, P [dimensionless] is the soil support practices or erosion prevention practices factor (Renard et al., 1991).

Rainfall erosivity (370 electronic rain gauges) and soil erodibility (Panagos et al., 2014) were spatially described by means of a relevant number of statistical data and advanced interpolation techniques. For most of the rain gauges, continuous 30-min pluviograph data collected over ten years (2002–2011) were employed. Both factors were calculated using the methods reported in the USLE and USLE forest handbooks (Wischmeier and Smith, 1978; Dissmeyer and Foster, 1984). The topographic conditions of the forest land were obtained using a 25-m spatial resolution Digital Terrain Model (DTM). Remotely sensed data were employed to describe the spatial variability of the tree crown conditions and percentage of bare soil. This information was elaborated to estimate the C factor according to guidelines proposed by Dissmeyer and Foster (1984) to run the USLE for forested areas. The impacts attributable to forest-logging activities were taken into account. The P-factor values were calculated based on data received through the observation of 500 clear-cut areas that were randomly distributed across the country. A complete description of the methodology is given in the supplementary materials.

## 4. Results

### 4.1. Map of the Italian coppice forest clear-cuts

The mapping operations of human-induced forest changes covered a wooded surface of $785.6 \cdot 10^4$ ha for the period from June 2002 to August 2011 (total area monitored: $7858 \cdot 10^4$ ha). The remote sensing monitoring analyses showed that an estimated 317,535 ha (125,272 clear-cut areas), or 4.04% of the monitored areas within the Italian forest lands, were affected by tree harvesting (Fig. 3). The annual rates of forest harvesting range from 0.3% (2008) to 0.5% (2002) (×31,750 ha; standard

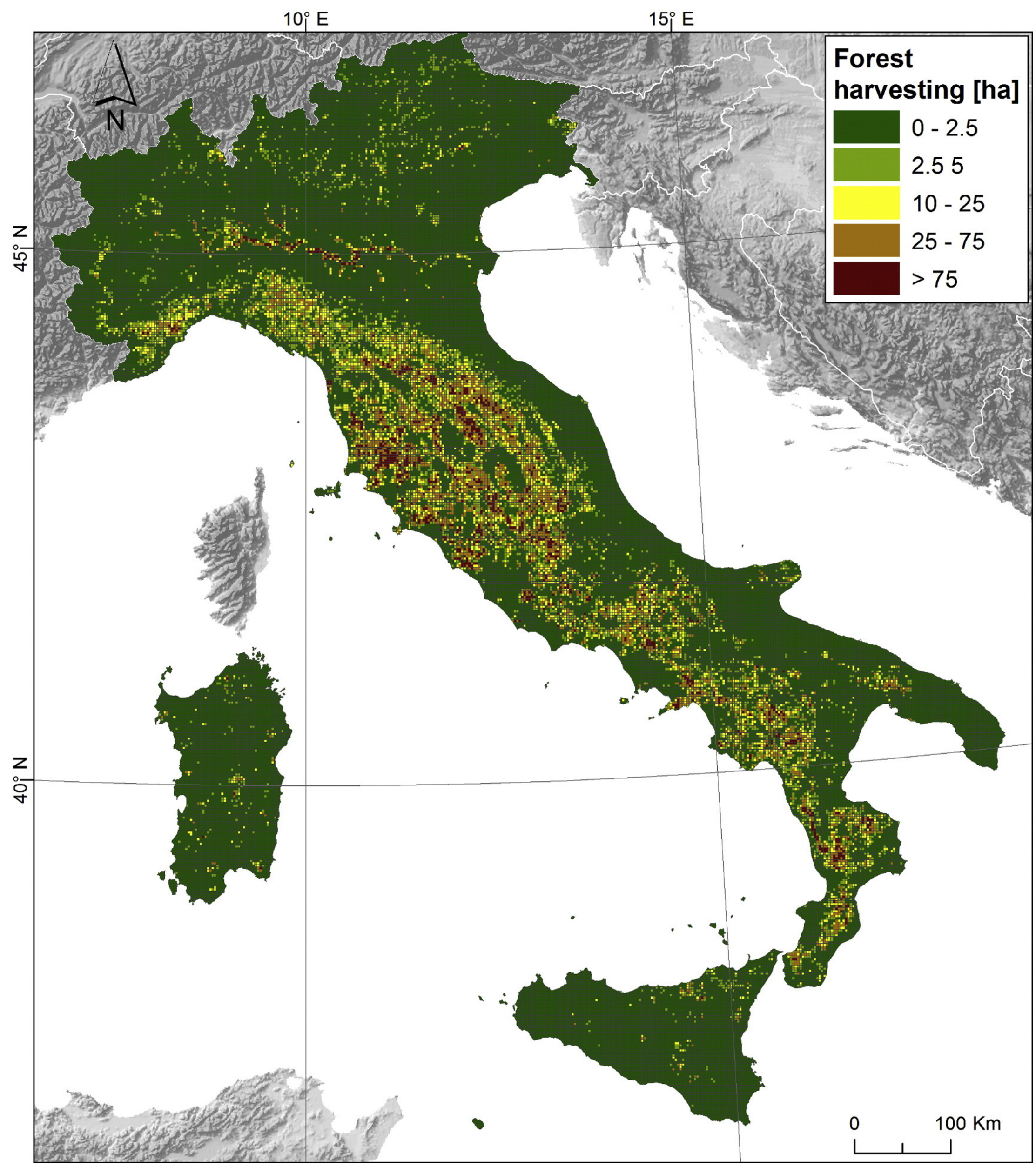


**Fig. 3.** Forest harvesting averaged by 2.5 × 2.5 km grid.

deviation (σ) 3357 ha). The greatest woodland changes occurred during 2002, involving a forest area of 36,933 ha (Table 3). With regard to the type of forest exploitation, the broad-leaved forest was the predominantly harvested forest type (293,171 ha; 92.3%) followed by mixed forests (7979 ha; 2.5%) and coniferous forests (16,385 ha; 5.2%).

Statistical operations in an ArcMap 10 environment revealed that about 93,539 ha, equal to 29.5% of the total detected forest changes, occurred in protected areas (i.e. Sites of Community Importance (SCI) and Special Protection Areas (SPA), as well as national and regional parks). At a regional level (EU NUTS2 level), Umbria (ITI2), Lazio (ITI4) and Tuscany (ITI1) were the most exploited wood extraction areas (11.2%, 10.5% and 8.2%, respectively). Despite their dense woods, Lombardy (ITC4), Liguria (ITC3) and Abruzzo (ITF1), by contrast, had the lowest clear-cut areas, accounting for 1.9%, 1.7% and 1.9%, respectively. Coppice-tree harvesting was found to be very low in Valle d'Aosta (ITC2), Friuli-Venezia Giulia (ITH4) and Trentino-South Tyrol (ITH1).

Most of the harvested areas were located in the mountains and hilly sectors of the Peninsula. About 35% of the clear-cut areas occurred on hillslopes with slope gradients ranging from moderate to steep (>20°). Here, the combination of steep slopes and high levels of precipitation compared to the national average (Panagos et al., 2015a; Panagos et al., 2015b) easily induces processes of soil degradation due to erosion (Sorriso-Valvo et al., 1995; Borrelli and Schütt, 2014).

Interestingly, it was found that clear-cut areas appeared in areas declared by the EU as Sites of Community Importance (SCI) and Special Protection Areas (SPAs) in the Natura 2000 network, as well as in national and regional parks. About 93,539 ha of forests were harvested in areas subject to natural protection, which is equal to 3% of the forested Natura 2000 area. A NUTS-2-level comparison showed that Umbria (ITI2) (9.3), Molise (ITF2) (8.1), Lazio (ITI4) (7.5%) and Campania (ITF3) (5.1%) had the highest forest change rates in the Natura 2000 areas.

### 4.2. Accuracy assessment

The thematic accuracy analysis showed that 75.5% (n 1140; x̄1x̄ ha; s 2 ha) of visually identified clear-cut areas (larger than 0.45 ha) were also present in our algorithm-derived clear-cut database. By contrast, 369 clear-cut areas (x̄1.4 ha; s 1.77 ha) detected by visual interpretation were not detected by the algorithmic study. The geometric calculations were carried out on a per-pixel basis for the 1140 clear-cut areas detected by both studies. The overall classification accuracy of the algorithm-derived clear-cut areas was 0.997, with a Kappa Index of Agreement (KIA) of 0.77.

### 4.3. Post-harvest vegetation development

The method employed to estimate the post-harvest USLE C factor assumes that, regarding the functional effectiveness of soil protection, a harvested coppice forest regains the coverage function of a moderately dense forest (i.e. a C of 0.009) four years after the clear-cut. Trend analyses of the Landsat NDVI and MODIS EVI were performed to ensure that the experiences gained from the experimental sites on the post-harvest vegetation development, and thus the derived C factor, were representative of the broader national conditions.

Fig. 4a provides an example of the post-harvest vegetation development, while Fig. 4b shows a line chart derived from the Landsat NDVI values of 250 clear-cut areas acquired during the growing season (2004–2009). The information in both of these figures is consistent with the post-harvest USLE C factor used for the modelling of this study. The undisturbed forests show an average NDVI value of 0.74. This value decreases by 34.1% during the first year after harvesting. Thereafter, the pre- versus post-harvest delta was 10.2% during the second year, 8.2% during the third year and 1.7% during the fourth year after the cut. The NDVI shows quasi pre-harvesting values from the 49th month onwards. Similar dynamics of the post-harvest vegetation development were observed in the 16-day combined MODIS EVI time-series (Fig. 4c). In general, the EVI data offered a more extensive overview of the VI dynamics for the entire year.

### 4.4. Long-term Italian forest logging

A 20-year period of forest logging was simulated following the insights gained from the mapping activities (2002 to 2011). A set of about 250,000 clear-cut areas was simulated, which is equal to a land surface of about 517,176 ha. Accordingly, the total logging area for the 30-year period totalled about 834,711 ha (ca. 10.6% of the monitored forest), and 317,535 ha for the period 2002–2011.

### 4.5. Soil loss by water erosion

The modelling approach provided a prediction of the soil loss by water erosion for each of the 126 million cells into which the Italian forests were subdivided (25 × 25 m cell-size). The predicted long-term average soil loss rate was 0.54 Mg $ha^{-1}$ $yr^{-1}$ (σ 0.92 Mg $ha^{-1}$ $yr^{-1}$).

Fig. 5 shows the soil loss rates subdivided into five classes set to highlight soil erosion dynamics in forestlands. Modelling the data based on the more traditional seven-class approach (Borrelli et al., 2014b), about 88.4% and 8.8% of the study area were found to fall into the very low (0–1 Mg $ha^{-1}$ $yr^{-1}$) and low (1–3 Mg $ha^{-1}$ $yr^{-1}$) erosion classes 1 and 2, respectively. From this it follows that the soil loss rates in large parts of Italian forest land did not exceed 3 Mg $ha^{-1}$ $yr^{-1}$. Moderate (class 3, 3–5 Mg $ha^{-1}$ $yr^{-1}$) and high (class 4, 5–10 Mg $ha^{-1}$ $yr^{-1}$) erosion values were simulated for 2.1% and 0.6% of the study area, respectively. The remaining area (0.1%) (classes 5–7) exceeded the tolerable soil loss threshold (T) specified for Mediterranean environments (10 Mg $ha^{-1}$ $yr^{-1}$). Beyond this threshold, a progressive decrease in the soil's ability to sustain vegetation and livestock can be observed. These high-impact and severe forms of erosion are primarily located along the Apennines, where forest logging and sparsely vegetated areas on steep slopes cause intense soil mobilisation.

The average soil loss rate in forests that remained undisturbed during the modelling period is equal to 0.33 Mg $ha^{-1}$ $yr^{-1}$ (σ0.32 Mg $ha^{-1}$ $yr^{-1}$). About 54.7% of the total long-term soil loss was predicted in the undisturbed forests. The logged areas account for 45.3% of the predicted soil loss (quantitatively equal to 30.789 x $10^6$ Mg $yr^{-1}$ and 2.31 Mg $ha^{-1}$ $yr^{-1}$, with a σ of 1.87 Mg $ha^{-1}$ $yr^{-1}$). Notably, about half of the soil loss (45.3%) was predicted for the logged areas, although these covered only about 10.6% of Italian forest land area.

The average soil loss rate during the first four years after the vegetation disturbance was 13.9 Mg $ha^{-1}$ $yr^{-1}$ (34.4% predicted in the mapped areas and 65.6% predicted in the simulated area). Here, the time in years after the clear-cut appears to be the primary factor that influences the level of the predicted soil erosion values. The low soil loss rates of densely covered forest land increase to an average value of 25.66 Mg $ha^{-1}$ $yr^{-1}$ during the first twelve months after the clear-cut.

**Table 3**
Descriptive statistics of the forest harvesting by year.

| Year | Harvested area | Clear-cut areas |
|---|---|---|
| | [ha] | [n] |
| 2002 | 36,933 | 14,866 |
| 2003 | 32,712 | 13,307 |
| 2004 | 29,811 | 11,548 |
| 2005 | 30,159 | 11,822 |
| 2006 | 30,885 | 12,117 |
| 2007 | 29,051 | 12,470 |
| 2008 | 24,737 | 8278 |
| 2009 | 34,626 | 13,568 |
| 2010 | 34,182 | 14,131 |
| 2011 | 34,439 | 13,165 |
| Total | 317,535 | 125,272 |

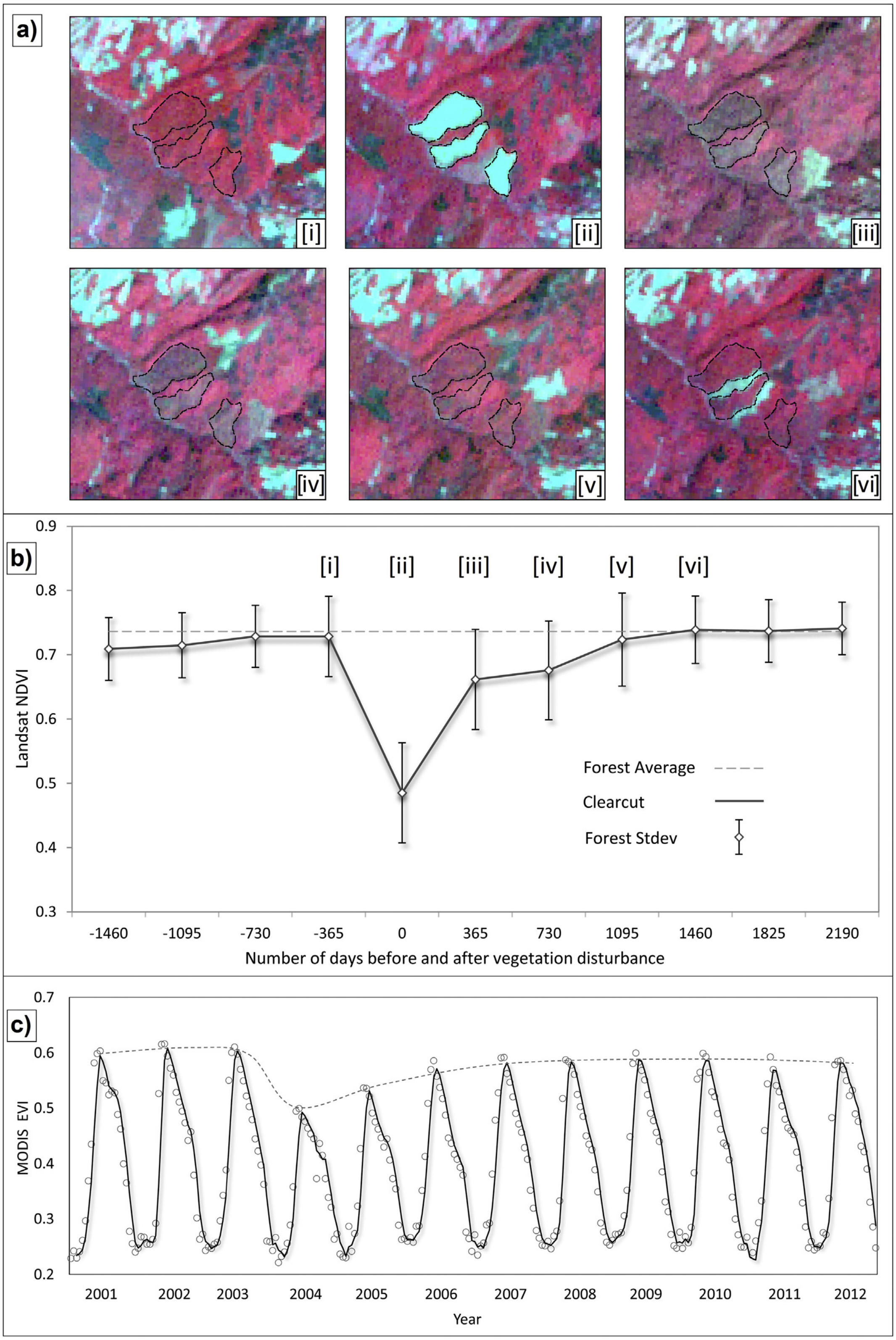


**Fig. 4.** Post-harvest vegetation development. (a) Landsat false-colour time-series (bands 4/3/2) for the period from Summer 2004 (i) to Summer 2009 (iv) (Path 192 Row 30 — Tuscany). (b) Average Landsat NDVI time-series for 250 clear-cut areas spread across the country. (c) Average MODIS EVI 16-day time-series extracted by the JRC Phenolo model for 510 clear-cut areas spread across the country (the continuous line indicates the moving average). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The soil loss rates remain high during the second year after the cut, with an average value of 17.59 Mg ha$^{-1}$ yr$^{-1}$, but start to decrease steadily during the third year after the clear-cut (average of 11 Mg ha$^{-1}$ yr$^{-1}$).

The sediment budget analysis revealed that around 37.1% of the total soil loss due to accelerated soil erosion processes in disturbed forests occurs during the first 12 months after the tree harvesting.

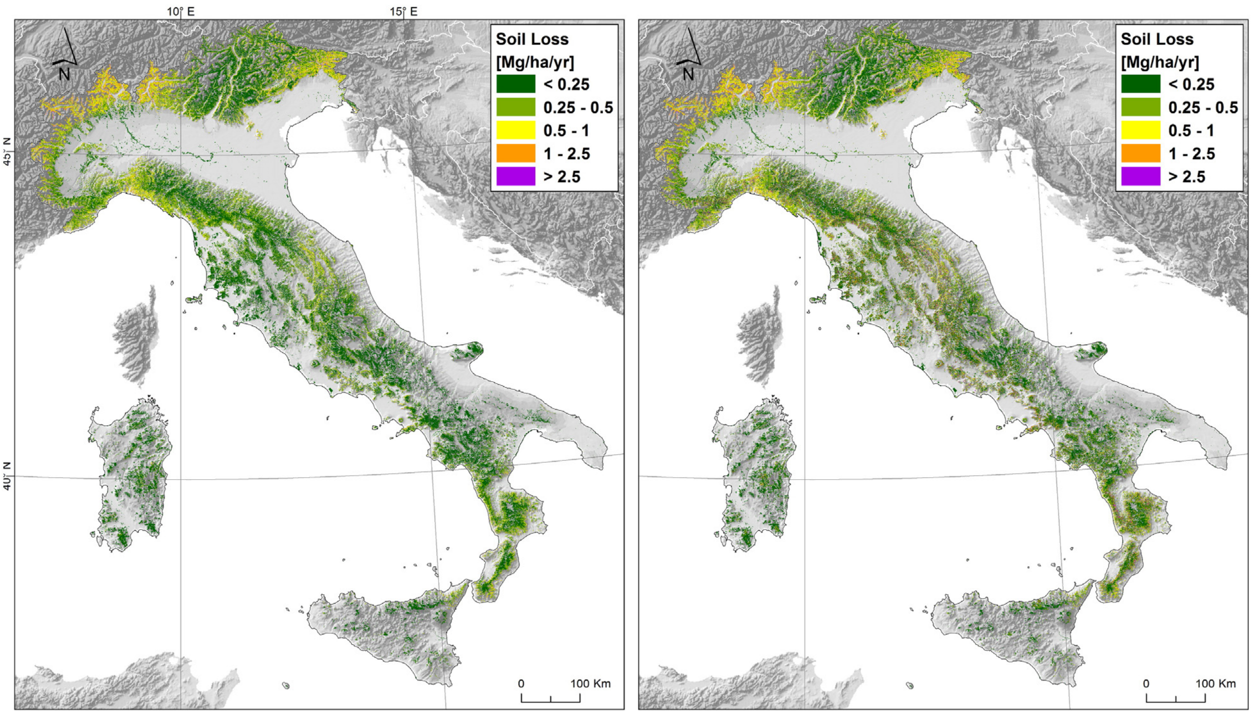


**Fig. 5.** Average long-term soil loss potential modelled assuming the absence (left) and presence (right) of forest harvesting activities.

At a regional (NUTS 2) level, the highest average soil loss rate can be found in Valle d'Aosta (ITC2) (1.07 Mg ha$^{-1}$ yr$^{-1}$), followed by Friuli Venezia Giulia (ITH4) (0.56 Mg ha$^{-1}$ yr$^{-1}$), Piedmont (ITC1) (0.53 Mg ha$^{-1}$ yr$^{-1}$) and Lombardy (ITC4) (0.49 Mg ha$^{-1}$ yr$^{-1}$). The lowest average soil loss rates appeared in Apulia (0.11 Mg ha$^{-1}$ yr$^{-1}$), Molise (ITF2) (0.15 Mg ha$^{-1}$ yr$^{-1}$) and Sardinia (ITG2) (0.16 Mg ha$^{-1}$ yr$^{-1}$).

The average soil loss rate predicted in the Natura 2000 wooded areas was 1.99 Mg ha$^{-1}$ yr$^{-1}$ (152,800 Mg yr$^{-1}$). An additional USLE model run for disturbed forest lands, which assumed the absence of forest harvesting activities, resulted in an average soil loss of 0.18 Mg ha$^{-1}$ yr$^{-1}$ (14,000 Mg yr$^{-1}$). In comparison with the forest-harvesting condition, the soil loss rate generated by the no-forest harvesting scenario was ten times lower, with larger decreases occurring in Liguria (ITC3), Veneto (ITH3), Abruzzo (ITF1) and Tuscany (ITI1).

## 5. Discussion

Italian forest land is an important ecosystem in terms of biodiversity, timber and carbon storage and recreational aspects (INFC, 2005, 2007). Like all of the other Member States of the European Union, Italy is committed to the maintenance and protection of its forests (Forestry Strategy, 1998; EU Forest Action Plan, 2006). Despite the ongoing intensive exploitation of Italian forest resources (Eurostat, 2014; Istat, 2014) and its documented impacts (Porto et al., 2009; Borrelli et al., 2013a; Marcantonio et al., 2013), researchers still lack a well-grounded knowledge about the effects that the forest management practices have on soils and their related functions. This lack of knowledge is an obstacle to the formation of scientifically proven recommendations, and thus prevents national and European institutions from taking actions to mitigate land degradation.

The remote-sensing and GIS-based analysis presented in this study was designed to move a step further towards filling this knowledge gap. It aimed to identify the areas that are prone to soil erosion, understand the magnitude of the natural constricting forces, and evaluate the effects of the current wood-logging system in order to provide national and European decision makers with scientifically proven and effective recommendations.

### 5.1. Forest monitoring

To enable the modelling of soil erosion, both the forest status and the forest harvest events were carefully mapped. The methodology provided a consistent and spatially precise indication of the annual forest cover changes at the national scale across time using an eleven-year Landsat time-series (2002–2011). With a minimum mapping unit of 0.45 ha (five 30 × 30 m Landsat pixels), the study outcomes are in line with the international forestry monitoring standards (Vidal et al., 2008). The thorough semi-automatic rectification procedures, including a multi-scale (i.e. 1:20,000, 1:10,000, and 1:5000) on-screen visual interpretation analysis of the results based on aerial orthophotos, allowed for the effective selection of forest logging areas (Borrelli et al., 2014a). False indications of forest logging that often appear in automatic mapping processes (Roy and Boschetti, 2009) were filtered out to ensure thorough mapping of the area. More than 120,000 individual clear-cut areas were mapped across an overall monitored surface of about 78 million hectares with a good thematic (75.5%) and geometric accuracy (KIA = 0.77).

The analysis of the forest management statistics provided by the Italian National Institute of Statistics (Istat, 2014) (Table 4) showed that: i) the study area covers about 75% of the total national wooded land, ii) 66% of Italian wooded land is privately owned, iii) 42% of the forest surface is currently managed as coppice forest, iv) the average logging surface in Italy is 1.03 ha, v) 33.9% of harvested trees come from public areas, with an average logging surface of 2.8 ha, and vi) 66.1% of harvested trees come from private forests, with an average logging surface of 0.8 ha.

A comparison of this information with the study results shows that, despite the fact that 75% of the national wooded surface was investigated, the mapped clear-cut areas cover only about 35.2% of the total harvested surface reported in the national statistics. The presence of potentially unmapped clear-cut areas due to Landsat data gaps was reduced to a minimum by the methods employed (Borrelli et al., 2013c),

Please cite this article as: Borrelli, P., et al., Assessment of the impacts of clear-cutting on soil loss by water erosion in Italian forests: First comprehensive monitoring and mo..., Catena (2016), http://dx.doi.org/10.1016/j.catena.2016.02.017

**Table 4**
Descriptive statistics of the forest harvest reported by the National Institute of Statistics (Istat, 2014).

| Year | Private forest | | | Public forest | | |
|---|---|---|---|---|---|---|
| | Harvest surface [ha] | Number of cuts | Average [ha] | Harvest surface [ha] | Number of cuts | Average [ha] |
| 2002 | 29,118 | 8856 | 3.29 | 62,684 | 86,460 | 0.73 |
| 2003 | 34,558 | 8706 | 3.97 | 65,631 | 86,026 | 0.76 |
| 2004 | 32,030 | 9067 | 3.53 | 66,032 | 87,337 | 0.76 |
| 2005 | 29,772 | 8587 | 3.47 | 64,600 | 78,171 | 0.83 |
| 2006 | 30,824 | 10,702 | 2.88 | 64,347 | 78,862 | 0.82 |
| 2007 | 27,754 | 8420 | 3.30 | 63,634 | 79,360 | 0.80 |
| 2008 | 29,395 | 8251 | 3.56 | 54,618 | 69,058 | 0.79 |
| 2009 | 30,562 | 7685 | 3.98 | 58,763 | 72,960 | 0.81 |
| 2010 | 38,359 | 30,421 | 1.26 | 45,337 | 47,794 | 0.95 |
| 2011 | 23,774 | 8766 | 2.71 | 50,024 | 73,710 | 0.68 |

which left an unmapped area of only about 5% of the studied area (2% due to ETM + gaps and 3% due to cloud cover). The accuracy assessment and further analyses ensured that about 75% of the clear-cut areas of more than 0.5 ha were detected. It proved to be difficult to accurately detect clear-cut areas of between 0.5 and 1.5 ha (ca. 20% of the total mapped harvests) using Landsat imagery. Given their small sizes, such harvests were generally underestimated, and are recognised as the primary source of the 25% of harvests omitted. A further analysis showed that a large part of the difference between the mapped surface and the statistical data was due to the marked occurrence of harvests in private forests (about two-thirds of the total), which show small clear-cut areas (×0.8 ha). Small clear-cuts are generally preferred by private owners because, according to the autonomous regional policies in most Italian administrative regions, the only requirement for harvesting coppice areas smaller than 0.5–3 ha is the submission of a simple declaration by the forest owner to the Italian State Forest Service (Corpo Forestale dello Stato). According to the statistical data available, one can suppose that the 64.8% difference (584,281 ha) between the data of Istat (2014) and this study can be explained as follows:

- 25% (225,454 ha) is due to the omission error of the proposed methods;
- 5% (45,091 ha) is potentially due to the unmapped forest falling within Landsat data gaps;
- 10 to 20% (90,182 to 180,363 ha) is due to the clear-cuts that could not been mapped as they are smaller than 0.5 ha;
- The remaining 15 to 25% (135,272 to 225,454 ha) is due to the logging activities carried out on other wooded lands that were not investigated in this study (displayed by the CORINE 2006 database as 321, 322, 323 and 324).

## 5.2. Soil erosion

### 5.2.1. Modelling approach

The soil erosion modelling exercise was carried out following the methods proposed for USLE (Wischmeier and Smith, 1978) including subsequent improvements (Dissmeyer and Foster, 1984; Renard et al., 1997). The best available spatial information for Italy was used to create the set of spatial (LS, K and P factor) and temporal (R and C factor) model input variables. When a complex geomorphic process such as soil loss is modelled, the employment of qualitatively and spatially adequate input data is an essential precondition for achieving reliable and robust model outcomes (van Rompaey et al., 2003; van Oost et al., 2005b). The high spatial resolution DEM (25 × 25 m cell size) allowed us to also take into account smaller-scale relief features in this national-scale study. This is extremely important in order to accurately derive the local topographical and hydrological features (Zhang et al., 2008) that play a major role in the erosive process (Mitas and Mitasova, 1998). The soil erodibility (K) was spatially defined at a resolution of 500 m, a scale suitable for the spatial variations of this environmental factor (McBratney et al., 2003). 370 meteorological stations were used to calculate the sub-hourly rainfall erosivity data (covering the forest change monitoring period 2002–2011). For the first time, the rainfall erosivity dynamics were measured across the entire country following the original methods reported in the USDA handbooks. This represents a major improvement compared to previous studies (e.g. Van der Knijff et al., 1999, Grimm et al., 2003) that modelled USLE-based soil loss at the Italian scale using rainfall erosivity computed from rainfall volumes instead of rainfall intensity (Diodato and Bellocchi, 2010; Diodato and Soriano, 2014). With regard to the land cover and management factor (C), the scheme proposed by Dissmeyer and Foster (1984) was followed. The P factor (soil conservation practices) was statistically approximated based on information acquired by visual interpretation of the aerial images. Unlike previous large-scale studies (e.g. Van der Knijff et al., 1999; Grimm et al., 2003; Bosco, personal communication) where the C and P factors were kept constant for the entire forest land or were approximated with high uncertainty (De Jong, 1994), a novel approach that aimed to spatially describe the different forest canopy cover conditions was tested here. As for the different agricultural plant types (Wischmeier and Smith, 1978; Panagos et al., 2015c), different tree species and forest conditions involve different degrees of soil protection and soil loss rates (Dissmeyer and Foster, 1984). For the Italian forests, a significant spatial influence of the C factor was observed, ranging from 0.0005 to 0.007 ($\bar{x} = 0.0015$, $\sigma = 0.0005$).

### 5.2.2. Soil erosion susceptibility of Italian forests

The average soil loss in forests which remained undisturbed during the modelling period shows that Italian forests are moderately effective (0.33 Mg ha$^{-1}$ yr$^{-1}$) in reducing soil erosion compared to other European and American forests (Hood et al., 2002; Cerdan et al., 2010). The modelling results are higher than the average value measured through plot experiments in both Mediterranean Europe (0.18 Mg ha$^{-1}$ yr$^{-1}$ measured in 552 plot-months; Cerdan et al., 2010) and other European regions (0.003 Mg ha$^{-1}$ yr$^{-1}$ measured in 60 plot-months; Cerdan et al., 2010). However, this situation is in line with the higher sediment yield values generally measured in Italian forested watersheds (Bazzoffi et al., 1996; de Vente et al., 2006). The high soil loss rates reflect the heterogeneity and propensity of the landscape to erosion, where in some areas the annual average rainfall erosivity can be as high as ca. 6000 MJ mm ha$^{-1}$ h$^{-1}$ yr$^{-1}$ ($\sigma = 1286$ MJ mm ha$^{-1}$ h$^{-1}$ yr$^{-1}$) and the forest slopes can exceed 25% (62.2% of the study area, of which 25.5% of the slopes are greater than 45%). The erosive power of rainfall in Italian forests is 2.5 times higher than the average for European forests (697.6 MJ mm ha$^{-1}$ h$^{-1}$ y$^{-1}$) and almost twice the average of the Mediterranean countries. In addition, the topographical factor (LS) of the Italian forests is the highest in Europe (6.5 [dimensionless]) and is considerably higher than in other Mediterranean European countries (Greece 5.9; Spain 4; France 2.9; Croatia 2.9). The average C-factor value of Italian forests is 0.00154, 35% higher than the average European forest C factor (0.00116). There are no significant differences between the soil erodibility factors (K) of Italian (0.022 Mg h$^{-1}$ MJ$^{-1}$ mm$^{-1}$) and European forest soils (0.024 Mg h$^{-1}$ MJ$^{-1}$ mm$^{-1}$). Overall, the magnitude of natural triggering forces makes the Italian forests the most susceptible to erosion in Europe.

### 5.2.3. USLE soil loss prediction

Higher soil loss rates were generally observed along the Apennines, the Alps and the surrounding hilly areas, while lower values were predicted for the Apulian plateau, the Po valley, along the Tyrrhenian coast and the Italian islands (Fig. 5). The highest soil loss rates occurred in mountainous areas in the north of the country with a high incidence of steep slopes and where the rain hits the ground with high energy (e.g. Valle d'Aosta (ITC2), Friuli Venezia Giulia (ITH4), north-western

Please cite this article as: Borrelli, P., et al., Assessment of the impacts of clear-cutting on soil loss by water erosion in Italian forests: First comprehensive monitoring and mo..., Catena (2016), http://dx.doi.org/10.1016/j.catena.2016.02.017

Lombardy (ITC4), north-eastern Piedmont (ITC1) and eastern Liguria (ITC3)).

Considering only the harvested areas, the soil loss rates, although accelerated, followed the general dynamics described above, highlighting the dominant role of the magnitude of natural triggering forces. In absolute terms, however, the highest human-induced soil loss by water erosion occurred in the most intensely harvested administrative regions (NUTS-2), i.e. Tuscany ($275.7 \times 10^4$ Mg $yr^{-1}$), Lazio ($166.2 \times 10^4$ Mg $yr^{-1}$), Umbria ($141.8 \times 10^4$ Mg $yr^{-1}$) and Calabria ($112.8 \times 10^4$ Mg $yr^{-1}$) (Table 5). The low soil loss rates of the undisturbed forests (0.33 Mg $ha^{-1}$ $yr^{-1}$) rose to an average value of 2.31 Mg $ha^{-1}$ $yr^{-1}$ in the clear-cut areas (13.9 Mg $ha^{-1}$ $yr^{-1}$ during the first four years after harvesting). Most of the soil erosion took place during the first twelve months after harvesting (25.66 Mg $ha^{-1}$ $yr^{-1}$), when the development of grass vegetation was still reduced. Therefore, soil loss rates peaked during the first year after harvesting and then gradually decreased by year two, following the dynamics observed in the field (Garfì et al., 2006; Borrelli and Schütt, 2014). This was in accordance with both the modelling approaches based on the USLE model (Hood et al., 2002) and the field observations carried out of forest lands in other regions (Lal, 1996; Edeso et al., 1999; Kitahara et al., 2000; Callegari et al., 2001). The post-harvest vegetation development observed using Landsat and MODIS time-series confirmed the congruence between the vegetation indices and the release of the modelled sediment.

Notably, a recorded forest disturbance involving about 10.6% of the simulated area resulted in about 45.3% of the total soil loss. Following the forest monitoring analysis reported in Section 5.1, about 40 to 50% of harvests that occurred in the study area were not detected, and consequently were not modelled, due to limits of the Landsat imagery to accurately detect small clear-cut areas (Borrelli et al., 2013c). A large forest surface that, if considered in the modelling operations, would further exacerbate the soil loss predictions. A simple statistical approach was used to estimate the total soil loss from forest areas considering that: i) the total harvested surface is provided by the national statistics (Istat, 2015), ii) the average soil loss rates predicted for the undisturbed (0.33 Mg $ha^{-1}$ $yr^{-1}$) and disturbed forest (2.31 Mg $ha^{-1}$ $yr^{-1}$) are known, and iii) in a first approximation, the unmapped harvests can be assumed to be adjacent or near to the mapped harvests, and to show similar erosion dynamics. Following this hypothesis, the total soil loss in the forests would increase by 14.9% (equal to $10.1 \times 10^3$ Mg $yr^{-1}$). The disturbed forest area would amount to 15.4%, which would be responsible for about 55.9% of the total soil loss.

**Table 5**
Descriptive statistics of the soil loss in the clear-cut areas of the Italian regions (NUTS-2).

| Region name | NUTS-2 [code] | Simulation area [ha] | Soil loss rate Mg $ha^{-1}$ $yr^{-1}$ | Soil loss Mg $yr^{-1}$ |
|---|---|---|---|---|
| Piedmont | ITC1 | 5305 | 3.2 | 270,818 |
| Valle d'Aosta | ITC2 | 17 | 8.1 | 2289 |
| Liguria | ITC3 | 5739 | 3.5 | 318,339 |
| Lombardy | ITC4 | 14,259 | 1.0 | 222,817 |
| Abruzzo | ITF1 | 6038 | 1.9 | 187,448 |
| Molise | ITF2 | 8845 | 1.1 | 161,099 |
| Campania | ITF3 | 25,125 | 2.1 | 858,568 |
| Puglia | ITF4 | 3960 | 0.6 | 37,326 |
| Basilicata | ITF5 | 14,885 | 1.0 | 236,501 |
| Calabria | ITF6 | 25,583 | 2.8 | 1,128,802 |
| Sicilia | ITG1 | 2517 | 1.3 | 52,771 |
| Sardegna | ITG2 | 3033 | 1.1 | 53,765 |
| Trentino-Alto Adige | ITH1/2 | 2087 | 2.6 | 86,320 |
| Veneto | ITH3 | 1981 | 3.2 | 100,460 |
| Friuli-Venezia Giulia | ITH4 | 583 | 5.9 | 54,716 |
| Emilia-Romagna | ITD5 | 19,305 | 1.8 | 547,782 |
| Toscana | ITI1 | 84,549 | 2.0 | 2,757,715 |
| Umbria | ITI2 | 35,833 | 2.5 | 1,418,815 |
| Marche | ITE3 | 8079 | 3.3 | 424,662 |
| Lazio | ITI4 | 49,387 | 2.1 | 1,662,250 |

## 6. Conclusions

The Member States of the European Union have committed to the maintenance and protection of their forests (Forestry Strategy, 1998; EU Forest Action Plan, 2006) and to implement adequate measures to meet water quality targets in freshwater bodies (European Water Framework Directive, 2000/60/EC). In this context, soil erosion, especially when accelerated, can represent a serious threat to both soil-related forest ecosystems and aquatic ecosystems. The results of the 5th Ministerial Conference on the Protection of Forests in Europe (MCPFE, 2007) reported satisfactory conditions and the sustainable management of European forests. However, the MCPFE (2007) also reported that tree harvesting and forest operation damages are a source of severe economic losses, and can lead to deteriorations in the health and vitality of ecosystems in specific areas. So far, the monitoring of the status of the forest soils has been limited to ground-based surveys. The continuous and complete monitoring of forests is not economically feasible. As a consequence, traditional monitoring practices cannot be used to develop comprehensive knowledge about the environmental impacts of forestry practices such as clear-cutting. Therefore, a well-calibrated model would provide a promising alternative diagnostic tool to quantitatively assess the soil loss dynamics in European forests in order to monitor forest harvesting developments. The remote sensing monitoring analyses carried out in this study showed that 317,535 ha (125,272 clear-cut areas) of forest lands were subjected to tree harvesting, of which 29.5% were located within protected areas (Natura 2000). Modelled outcomes showed that the predicted soil loss by water erosion from the harvested forest (equal to 10.6% of the simulated area) potentially produced mobilised soil particles equal to 45% of the amount mobilised in the total forest land area. This study, which combined a high-resolution USLE model with remote sensing and interpolation techniques, shows that such a method (which undoubtedly can be further refined and developed) can provide more cost-effective and comprehensive monitoring of soil erosion processes in forests.

## Acknowledgements

The authors would like to thank Gráinne Mulhern for the revision of the article from a linguistic point of view.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.catena.2016.02.017.

## References

APAT, 2005. In: Compagnoni, B., Galluzzo, F. (Eds.), Carta Geologica d'Italia in scala 1:1.250,000. APAT — Servizio Geologico d'Italia, Rome.
Aronoff, S., 1982. Classification accuracy: a user approach. Photogramm. Eng. Remote. Sens. 48, 1299–1307.
Bagarello, V., Ferro, V., 2010. Analysis of soil loss data from plots of differing length for the Sparacia experimental area, Sicily, Italy. Biosyst. Eng. 105, 411–422.
Bazzoffi, P., Baldassarre, G., Vacca, S., 1996. Validation of PISA2 model for automatic assessment of reservoir sedimentation. In: Albertson, M. (Ed.), Proceedings of the International Conference on Reservoir Sedimentation. Colorado State University, pp. 519–528.
Borrelli, P., Schütt, B., 2014. Assessment of soil erosion sensitivity and post-timber-harvesting erosion response in a mountain environment of Central Italy. Geomorphology 204, 412–424.
Borrelli, P., Märker, M., Schütt, B., 2013a. Modelling post-tree-harvesting soil erosion and sediment deposition potential in the Turano River Basin (Italian Central Apennine). Land Degrad. Dev. 356–366.
Borrelli, P., Hoelzmann, P., Knitter, D., Schütt, B., 2013b. Late Quaternary soil erosion and landscape development in the Apennine region (central Italy). Quat. Int. 312, 96–108.
Borrelli, P., Sandia Rondón, L.A., Schütt, B., 2013c. The use of Landsat imagery to assess large-scale forest cover changes in space and time, minimizing false-positive changes. Appl. Geogr. 41, 147–157.
Borrelli, P., Modugno, S., Panagos, P., Marchetti, M., Schütt, B., Montanarella, L., 2014a. Detection of harvested forest areas in Italy using Landsat imagery. Appl. Geogr. 48, 102–111.

Borrelli, P., Märker, M., Panagos, P., Schütt, B., 2014b. Modelling soil erosion and river sediment yield for an intermountain drainage basin of the Central Apennines Italy. Catena 114, 45–58.

Borselli, L., Cassi, P., Torri, D., 2008. Prolegomena to sediment and flow connectivity in the landscape: a GIS and field numerical assessment. Catena 75, 268–277.

Callegari, G., Iovino, F., Mendicino, V., Veltri, A., 2001. Hydrological balance and soil erosion in Eucalyptus coppices. Proceedings of the International Conference: "Eucalyptus in the Mediterranean basin: Perspectives and new utilization". Centro Promozione Pubblicità, Firenze, pp. 283–329.

Cerdan, O., Poesen, J., Govers, G., Saby, N., Le Bissonnais, Y., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F.P.M., Roxo, M.J., 2006. Sheet and rill erosion. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley, Chichester, pp. 501–513.

Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F.J.P.M., Raclot, D., Ionita, I., Rejman, J., Rousseva, S., Muxart, T., Roxo, M.J., Dostal, T., 2010. Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. Geomorphology 122, 167–177.

Chavez, P.S., Mackinnon Jr., D.J., 1994. Automatic detection of vegetation changes in the southwestern United States using remotely sensing images. Photogramm. Remote Sens. 60, 571–583.

Chirici, G., Corona, P., Marchetti, M., Maselli, F., Bottai, L., 2011. Spatial distribution modelling of forest attributes coupling remotely sensed imagery and CIS techniques. In: Amaro, A., Reed, D., Soares, P. (Eds.), Modelling Forest Systems, Oxford, pp. 41–50.

De Jong, S.M., 1994. Derivation of vegetative variables from a Landsat TM image for erosion modelling. Earth Surf. Process. Landf. 19, 165–178.

de Vente, J., Poesen, J., Bazzoffi, P., Rompaey, A.V., Verstraeten, G., 2006. Predicting catchment sediment yield in Mediterranean environments: the importance of sediment sources and connectivity in Italian drainage basins. Earth Surf. Process. Landf. 3, 1017–1034.

Della Seta, M., Del Monte, M., Fredi, P., Palmieri, E.L., 2009. Space–time variability of denudation rates at the catchment and hillslope scales on the Tyrrhenian side of Central Italy. Geomorphology 107, 161–177.

Derose, R.C., Trustrum, N.A., Blaschke, P.M., 1993. Post-deforestation soil loss from steepland hillslopes in Taranaki, New Zealand. Earth Surf. Process. Landf. 18, 131–144.

Diodato, N., Bellocchi, G., 2010. MedREM, a rainfall erosivity model for the Mediterranean region. J. Hydrol. 387, 119–127.

Diodato, N., Soriano, M., 2014. Rainfalls and storm erosivity. In: N., Diodaton, Bellocchi, G. (Eds.), Storminess and Environmental Change. Springer, Netherlands, pp. 39–51.

Dissmeyer, G.E., Foster, G.R., 1984. A guide for predicting sheet and rillerosion on forest land. USDA For. Serv. Gen. Tech. Publ. R8-TP 6.

Edeso, J.M., Merino, A., Gonzalez, M.J., Marauri, P., 1999. Soil erosion under different harvesting managements in steep forestlands from northern Spain. Land Degrad. Dev. 10, 79–88.

EEA, European Environmental Agency, 2014. [Online] URL http://www.eea.europa.eu/data-and-map Accessed July 2014.

EU Forest Action Plan, 2006. [Online] URL http://ec.europa.eu/agriculture/fore/action_plan/index_en.htm.

Eurostat, 2013. Agriculture, Forestry and Fishery Statistics. 2013 ed Publications Office of the European Union, Luxembourg.

Eurostat, 2014. Forestry database. [Online] URL http://epp.eurostat.ec.europa.eu/portal/page/portal/forestry/data/database# Accessed May 2014.

Fabbio, G., 2010. Il ceduo tra passato e attualità: opzioni colturali e dinamica dendroauxonomica e strutturale nei boschi di origine cedua. In: Carraro, V., Anfodillo, T. (Eds.), Gestione multifunzionale e sostenibile dei boschi cedui: criticità e prospettive. TESAF Vol. 46, pp. 27–45.

Forestry Strategy, 1998. Council resolution on a forestry strategy for the European Union. Off. J. Eur. Communities 1–4 (Bruxelles).

Gamfeldt, L., Snäll, T., Bagchi, R., Jonsson, M., Gustafsson, L., Kjellander, P., Kjellander, P., Ruiz-Jaen, M.C., Fröberg, M., Stendahl, J., Philipson, C.C., Mikusiński, G., Andersson, E., Westerlund, B., Andrén, H., Moberg, F., Moen, J., Bengtsson, J., 2013. Higher levels of multiple ecosystem services are found in forests with more tree species. Nat. Commun. 4, 1340.

Garfì, G., Veltri, A., Callegari, G., Iovino, F., 2006. Effetti della ceduazione sulle perdite di suolo in popolamenti di castagno della Catena Costiera Cosentina (Calabria). Ital. J. For. Mt. Environ. 61, 507–531.

Glovis, 2014. Global visualization viewer. [Online] URL http://glovis.usgs.gov Accessed January 2014.

Greer, T., Sinun, W., Douglas, I., Bidin, K., 1996. Long term natural forest management and land-use change in a developing tropical catchment, Sabah, Malaysia. IAHS Publ. 236, 453–462.

Grimm, M., Jones, R.J., Rusco, E., Montanarella, L., 2003. Soil Erosion Risk in Italy: A Revised USLE Approach. Office for Official Publications of the European Communities, Luxembourg.

Hansen, M.C., Roy, D.P., Lindquist, E., Adusei, B., Justice, C.O., Altstatt, A., 2008. A method for integrating MODIS and Landsat data for systematic monitoring of forest cover and change in the Congo Basin. Remote Sens. Environ. 112, 2495–2513.

Hood, S.M., Zedaker, S.M., Aust, W.M., Smith, D.W., 2002. Universal soil loss equation (USLE) — predicted soil loss for harvesting regimes in Appalachian hardwoods. North. J. Appl. For. 19, 53–58.

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213.

INFC, 2005. Linee generali del progetto per il secondo inventario forestale nazionale italiano. Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio, MiPAF e Ispettorato Generale del Corpo Forestale dello Stato, CRAISAFA, Trento.

INFC, 2007. Le stime di superficie 2005. Ministero delle Politiche Agricole, Alimentari e Forestali, Ispettorato Generale e Corpo Forestale dello Stato, CRA e Istituto Sperimentale per l'Assestamento Forestale e l'Alpicoltura, Trento.

Iovino, F., Puglisi, S., 1991. L'aménagement des reboisements de protection. Un cas d'étude. 10th World Forestry Congress, Paris.

Istat, 2014. Dati statistici Foreste e silvicoltura. [Online] URL: http://agri.istat.it/sag_is_pdwout/jsp/Introduzione.jsp?id=7A Accessed February 2014.

Istat, 2015. Webpage. [Online] URL: http://www.istat.it/en/ Accessed February 2014. Accessed February 2015.

Jensen, J.R., 1986. Introductory Digital Image Processing. Prentice-Hall, New Jersey.

Kitahara, H., Okura, Y., Sammori, T., Kawanami, A., 2000. Application of universal soil loss equation (USLE) to mountainous forests in Japan. J. For. Res. 5, 231–236.

Lal, R., 1996. Deforestation and land-use effects on soil degradation and rehabilitation in Western Nigeria. I. Soil physical and hydrological properties. Land Degrad. Dev. 7, 19–45.

Marcantonio, M., Rocchini, D., Geri, F., Bacaro, G., Amici, V., 2013. Biodiversity, roads, & landscape fragmentation: two Mediterranean cases. Appl. Geogr. 42, 63–72.

Marker, M., Angeli, L., Bottai, L., Costantini, R., Ferrari, R., Innocenti, L., Siciliano, G., 2007. Assessment of land degradation susceptibility by scenario analysis: A case study in Southern Tuscany, Italy. Geomorphology 93, 120–129.

Marks, S.D., Rutt, G.P., 1997. Fluvial sediment inputs to upland gravel bed rivers draining forested catchments: potential ecological impacts. Hydrol. Earth Syst. Sci. 1, 499–508.

McBratney, A.B., Santos, M.M., Minasny, B., 2003. On digital soil mapping. Geoderma 117, 3–52.

MCPFE, 1993. Resolution H1 general guidelines for the sustainable management of forests in Europe. Second Ministerial Conference on the Protection of Forests in Europe 16–17 June 1993, Helsinki, Finland (5p. Retrieved February 22, 2010).

MCPFE — Ministerial Conference on Protection of Forests in Europe, 2007n. Fifth Ministerial Conference on the protection of Forests in Europe. Conference Proceedings, 5–7 November 2007, Warsaw, Poland.

Mitas, L., Mitasova, H., 1998. Distributed soil erosion simulation for effective erosion prevention. Water Resour. Res. 34, 505–516.

Morgan, R.P.C., 2005. Soil Erosion and Conservation. Blackwell Publishing, p. 299.

Ojea, E., Martin-Ortega, J., Chiabai, A., 2012. Defining and classifying ecosystem services for economic valuation: the case of forest water services. Environ. Sci. Pol. 19, 1–15.

Panagos, P., Meusburger, K., Ballabio, C., Borrelli, P., Alewell, C., 2014. Soil erodibility in Europe: A high-resolution dataset based on LUCAS. Sci. Total Environ. 479–480, 189–200.

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Tadić, M.P., Michaelides, S., Hrabalíková, M., Olsen, P., Aalto, J., Lakatos, M., Rymszewicz, A., Dumitrescu, A., Beguería, S., Alewell, C., 2015a. Rainfall erosivity in Europe. Sci. Total Environ. 511, 801–814.

Panagos, P., Borrelli, P., Meusburger, K., 2015b. A new European slope length and steepness factor (LS-factor) for modelling soil erosion by water. Geosciences 5, 117–126.

Panagos, P., Borrelli, P., Meusburger, K., Alewell, C., Lugato, E., Montanarella, L., 2015c. Estimating the soil erosion cover/managment factor at the European scale. Land Use Policy 48, 38–50.

Patrick, J.H., 1976. Soil erosion in the eastern forest. J. For. 10, 671–677.

Porto, P., Walling, D.E., Callegari, G., 2009. Investigating the effects of afforestation on soil erosion and sediment mobilisation in two small catchments in Southern Italy. Catena 79, 81–188.

Porto, P., Walling, D.E., Alewell, C., Callegari, G., Mabit, L., Mallimo, N., Zehringer, M., 2014. Use of a 137 Cs re-sampling technique to investigate temporal changes in soil erosion and sediment mobilisation for a small forested catchment in southern Italy. J. Environ. Radioact. 138, 137–148.

Potapov, P., Hansen, M.C., Stehman, S.V., Loveland, T.R., Pittman, K., 2008. Combining MODIS and Landsat imagery to estimate and map boreal forest cover loss. Remote Sens. Environ. 112, 3708–3719.

Renard, G., Foster, G.R., Weesies, G.A., Porter, J.P., 1991. RUSLE — revised universal soil loss equation. J. Soil Water Conserv. 46, 30–33.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook N.703. U.S. Department of Agriculture Research Service, Washington.

Roberts, R.G., Church, M., 1986. The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia. Can. J. For. Res. 16, 1092–1106.

Romero-Díaz, Alonso-Sarriá, F., Martínez-Lloris, M., 2007. Erosion rates obtained from checkdam sedimentation (SE Spain). A multi-method comparison. Catena 71, 172–178.

Roy, D.P., Boschetti, L., 2009. Southern Africa validation of the MODIS, L3JRC, and GlobCarbon burned-area products. Geosci. Remote Sens. 47, 1032–1044.

Silverman, B.W., 1986. Density estimation for statistics and data analysis. Monographs on Statistics and Applied Probability. Springer-Science, London, p. 176.

Singh, A., 1989. Digital change detection techniques using remotely-sensed data. Int. J. Remote Sens. 10, 989–1003.

Sorriso-Valvo, M., Bryan, R.B., Yair, A., Iovino, F., Antronico, L., 1995. Impact of afforestation on hydrological response and sediment production in a small Calabrian catchment. Catena 25, 89–104.

Stott, T., Leeks, G., Marks, S., Sawyer, A., 2001. Environmentally sensitive plot-scale timber harvesting: impact on suspended sediment. Bedload and bank erosion dynamics. J. Environ. Manag. 63, 3–25.

Swanston, D.N., 1991. Natural Processes. In: Meehan, W.R. (Ed.), Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitat: Special Publication 19. Bethesda, American Fisheries Society, Bethesda, pp. 139–180.

Swanston, D.N., Swanson, F.J., 1976. Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest. Geomorphol. Eng. 4, 199–221.

Please cite this article as: Borrelli, P., et al., Assessment of the impacts of clear-cutting on soil loss by water erosion in Italian forests: First comprehensive monitoring and mo..., Catena (2016), http://dx.doi.org/10.1016/j.catena.2016.02.017

Torri, D., Santi, E., Marignani, M., Rossi, M., Borselli, L., Maccherini, S., 2013. The recurring cycles of biancana badlands: erosion, vegetation and human impact. Catena 106, 22–30.

USGS, 2011. Landsat product type descriptions. [online] URL: http://edcsns17.cr.usgs.gov/helpdocs/landsat/product_descriptions.html [Accessed January 2014].

Vacca, A., Loddo, S., Ollesch, G., Puddu, R., Serra, G., Tomasi, D., Aru, A., 2000. Measurement of runoff and soil erosion in three areas under different land use in Sardinia (Italy). Catena 40, 69–92.

Vacchiano, G., Magnani, F., Collalti, A., 2012. Modelling Italian forests: state of the art and future challenges. iForest 5, 113–120.

Van der Knijff, J., Jones, R.J.A., Montanarella, L., 1999. Soil Erosion Risk Assessment in Italy. European Soil Bureau, European Commission, Luxemburg.

Van Oost, K., Govers, G., Quine, T.A., Heckrath, G., Olesen, J.E., De Gryze, S., Merckx, R., 2005a. Landscape-scale modelling of carbon cycling under the impact of soil redistribution: the role of tillage erosion. Glob. Biogeochem. Cycles 19, 1–13.

Van Oost, G., Govers, O., Cerdan, D., Thauré, A., Van Rompaey, A., Steegen, J., Nachtergaele, I., Takken, J., Poesen, J., 2005b. Spatially distributed data for erosion model calibration and validation: the Ganspoel and Kinderveld datasets. Catena 61, 105–121.

Van Rompaey, A.J.J., Bazzoffi, P., Jones, R.J.A., Montanarella, L., Govers, G., 2003. Validation of soil erosion risk assessments in Italy. European Soil Bureau Research Report No.12, EUR 20676 EN. Office for Official Publications of the European Communities, Luxembourg.

Vidal, C., Lanz, A., Tomppo, E., Schadauer, K., Gschwantner, T., di Cosmo, L., 2008. Establishing forest inventory reference definitions for forest and growing stock: a study towards common reporting. Silva Fenn. 42, 247–266.

Wall, D.H., Bardgett, R.D., Behan-Pelletier, V., Herrick, J.E., Jones, T.H., Six, J., Strong, D.R., 2013. Soil Ecology and Ecosystem Services. Oxford University Press.

Williams, M., 2003. Deforesting the Earth: From Prehistory to Global Crisis. University of Chicago Press.

Williams, D., 2006. Landsat-7 science data users handbook. [on line] URL http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_htmls/chapter11/chapter11.html [Accessed November 2011].

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses. Agriculture Handbook Vol. n. 537. Agriculture Research Service, US Department of Agriculture, Washington.

Zanchi, C., 1988. Soil loss and seasonal variation of erodibility in two soils with different texture in the Mugello valley in Central Italy. Catena Suppl. 12, 167–173.

Zhang, J.X., Chang, K.T., Wu, J.Q., 2008. Effects of DEM resolution and source on soil erosion modelling: A CASE study using the WEPP model. Int. J. Geogr. Inf. Sci. 22, 925–942.