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Effect of Good Agricultural and Environmental Conditions on erosion and soil organic carbon balance: A national case study

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ABSTRACT

Since, the Common Agricultural Policies (CAP) reform in 2003, many efforts have been made at the European level to promote a more environmentally friendly agriculture. In order to oblige farmers to manage their land sustainably, the GAEC (Good Agricultural and Environmental Conditions) were introduced as part of the Cross Compliance mechanism. Among the standards indicated, the protection of soils against erosion and the maintenance of soil organic matter and soil structure were two pillars to protect and enhance the soil quality and functions. While Member States should specifically define the most appropriate management practices and verify their application, there is a substantial lack of knowledge about the effects of this policy on erosion prevention and soil organic carbon (SOC) change. In order to fill this gap, we coupled a high resolution erosion model based on Revised Universal Soil Loss Equation (RUSLE) with the CENTURY biogeochemical model, with the aim to incorporate the lateral carbon fluxes occurring with the sediment transportation. Three scenarios were simulated on the whole extent of arable land in Italy: (i) a baseline without the GAEC implementation; (ii) a current scenario considering a set of management related to GAEC and the corresponding area of application derived from land use and agricultural management statistics and (iii) a technical potential where GAEC standards are applied to the entire surface. The results show a 10.8% decrease, from 8.33 Mg ha^{-1} year^{-1} to 7.43 Mg ha^{-1} year^{-1}, in soil loss potential due to the adoption of the GAEC conservation practices. The technical potential scenario shows a 50.1% decrease in the soil loss potential (soil loss 4.1 Mg ha^{-1} year^{-1}). The GAEC application resulted in overall SOC gains, with different rates depending on the hectares covered and the agroecosystem conditions. About 17% of the SOC change was attributable to avoided SOC transport by sediment erosion in the current scenario, while a potential gain up to 23.3 Mt of C by 2020 is predicted under the full GAEC application. These estimates provide a useful starting point to help the decision-makers in both ex-ante and ex-post policy evaluation while, scientifically, the way forward relies on linking biogeochemical and geomorphological processes occurring at landscape level and scaling those up to continental and global scales.

1. Introduction

Land degradation due to soil erosion is an old threat (Chapline, 1929; Ayres, 1936) which has turned into a major agricultural and environmental problem worldwide (Lal, 2014). The scientific community recognizes it as one of the most pressing environmental problems, because it can decrease agricultural productivity (Pimentel et al., 1995), degrade ecosystem functions (Foley et al., 2005), amplify hydrogeological risk (Poesen and Hooke, 1997) and, in severe cases, lead to displacement of human populations (Opie, 2000).

The ongoing erosion-associated loss of productivity has reduced the food supply capacities of many agricultural areas during the last few decades (Pimentel et al., 1995). Per capita shortages of arable land due to severe erosion and population growth have been observed in Africa, Asia and Europe (Lal, 1990). Despite the general increases in the agricultural production per capita (FAO,

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2015; Oldroyd, 2015), soil erosion and land degradation remain significant threats for most agricultural lands (Bai et al., 2008) and constitute a limiting factor for the per capita food production growth in several locations especially in the African countries (Nachtergaele et al., 2010; FAO, 2015).

Erosion rates accelerated by unsuitable land-use and management (Felix-Henningsen et al., 1997) affect soil fertility and productivity by reducing the water infiltration, water-holding capacity, organic matter, nutrients and organic biota (Morgan, 2009). The use of fertilization is an expensive practice that can partially mitigate the yield losses, however without stabilizing the erosion process. As a result, the soil is still moved by erosion carrying nutrients, pesticides, and other harmful farm chemicals into the receiving stream (Hodgkin and Hamilton, 1993; Novotny, 1999).

Recent studies have found that the mobilization and deposition of agricultural soils can also significantly alter nutrients and carbon cycling (Quinton et al., 2010), although the net effect of erosion and deposition in the carbon cycle is the subject of debate (Quine and Van Oost, 2007).

In eroding sites, the physical removal of SOC causes a depletion of the carbon pool, which may be partially compensated by the incoming fixed carbon (Kirkels et al., 2014). In addition considering the same depth, the exported SOC is replaced by more recalcitrant subsoil pools leading to complex feedbacks on vertical fluxes components (respiration and fixation). All these complex interactions still feed the dichotomous debate whether the erosion induces a net carbon source (Lal, 2004) or sink (Van Oost at el., 2005a).

Soils are the third largest global reservoir of carbon (Lal, 2004) and the largest terrestrial ecosystem sink or source of atmospheric CO_2 depending on land-use and management (Paustian et al., 1997; Houghton et al., 2012). In the last decades the use of process-based models has become a powerful approach to understand the main drivers of SOC dynamics, to provide new stock estimations and to make scenario analysis both at national/regional level (Van Wesemael et al., 2010; Álvaro-Fuentes et al., 2011) and at larger scale (Smith et al., 2005; Lugato et al., 2014a). However, the lateral carbon fluxes induced by the erosion, transport and deposition processes are often neglected in SOC models, since these geomorphological processes are generally known only at watershed level. While the coupling of SOC and erosion/transport models is not a technical limitation (Van Oost et al., 2005a,b), the lack of spatially-detailed information is still the major constraint to extend the simulation beyond small basins.

Soil erosion processes by water in European agricultural areas have been widely studied on a small scale (plots and hillslopes) and river basin scale (Kosmas et al., 1997; Hill and Schütt, 2000; De Vente and Poesen, 2005; Boardmann and Poesen, 2006; Verheijen et al., 2009; Cerdan et al., 2010), however, only few studies have been carried out at national and Pan-European scale. Van der Knijff et al. (2000) and Grimm et al. (2001) employed the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) to perform the first spatial distributed assessment of erosion by water in Italy and Europe. Despite the knowledge gained from these pioneering studies, the methods employed to compute the USLE parameters involved a large number of approximations and inconsistencies which affected the quality of the outcomes. Later, the Pan-European Soil Erosion Risk Assessment (PESERA; Kirkby et al., 2003), although employing a more advanced modelling scheme, used poor quality input data and a coarse spatial resolution (1 × 1 km) making this tool unsuitable for local land management planning.

Today, the mainstreaming of geospatial technologies like Geographic Information Systems (GIS), satellite imagery and robust spatial interpolation methods can facilitate the development of new highly accurate and spatially explicit approaches to assess soil erosion and land management practices (Van Rompaey et al., 2007; Salvati and Zitti, 2009; Borrelli et al., 2014; Panagos et al., 2014a, 2015a). The improvements in the recent years yielded encouraging results for the RUSLE implementation at basin and regional scale (Märker et al., 2008; Prasuhn et al., 2013; Borrelli and Schütt, 2014). The challenge of the immediate future for this area of research in soil erosion modelling is to adapt the broad improvements arising from local applications of RUSLE to large-scales in order to achieve more reliable soil loss predictions (Van Oost, 2005b) to be implemented in the scenarios analysis (Blanco-Canqui and Lal, 2008; Pelacani et al., 2008; Wauters et al., 2010).

The insights gained have helped to better quantify the essential role of soil conservation practices in order to develop strategies to reduce soil erosion (Pimentel, 1993), and the associated environmental costs. In the USA, the estimated cost of water erosion ranges from 12 to 42 billion US$ (Uri, 2000). Thanks to a series of conservation plans carried out under the technical assistance of the United States Department of Agriculture erosion rates have been considerably reduced. According to the National Resource Inventory of 2007 (USDA, 2014a), water-driven soil erosion on U.S. cropland decreased by 43% between 1982 and 2007 due to the measures of the Conservation Reserve Program (CRP) (USDA, 2014b).

In the EU, one of the main mechanisms to promote a more environmentally friendly agriculture was introduced by the CAP reform in 2003, through the so-called Cross Compliance mechanism. According to this new approach, the farmer support payments were conditioned with respect to environmental, animal welfare and food safety standards. This led to the definition of Good Agricultural and Environmental Conditions (GAEC), firstly established by Council Regulation No. 1782/2003 and subsequently Council Regulation (EC) No 73/2009. The prevention of soil erosion and maintenance of soil organic matter were two of GAEC requirements, which each Member State was obliged to address through national/regional standards such as: (i) minimal soil cover maintenance (GAEC 4); (ii) minimum land management reflecting site specific conditions to limit soil loss (GAEC 5) and (iii) maintenance of soil organic matter level through appropriate practices including ban on burning arable stubbles (GAEC 6) (MARS, 2014).

Although Member States are required to verify whether the farmers are compliant with the regulations (cross-compliance), the environmental effect of GAEC applications on erosion and carbon budgets are still unknown. Due to the large agricultural area, the different pedo-climatic conditions and the variety of farming systems across the EU, the effectiveness of GAEC can be only verified by assessing their actual effect on the environmental components. To reach this target more data, monitoring networks, remote sensing application and modelling tools are necessary.

For the first time, the present study deals with the assessment of the physical effect of GAEC standards application at the national-scale level, coupling a high resolution erosion model with an agro-ecosystem model of SOC dynamics. All arable land in Italy was selected as a study area because it is highly sensitive to erosion (Bagarello and Ferro, 2006), as it is repeatedly subject to prolonged dry periods followed by heavy bursts of intensive and erosive rainfalls falling on steep slopes with fragile soils (Torri et al., 2002; Diodato and Bellocchi, 2010; Borrelli et al., 2013). With respect to the identified research gap, this study aims to (i) produce a thorough RUSLE-based soil loss prediction with high spatial resolution; (ii) estimate the soil carbon stock variation including both lateral (by erosion) and vertical carbon fluxes; (iii) quantify the potential soil erosion and SOC response to the application of GAEC practices.

Table 1
Utilised agricultural area (UAA) in Italy and Europe, year 2012.

	Italy [1000 ha]	Europe
Utilised agricultural area	17,277	180,534
Arable land	12,885	111,627
	[%]	
Cereals	51.6	54.5
Dry pulse	2	1.6
Potatoes, sugar beet and others	1.4	3.3
Industrial plants	4.9	12.1
Fresh vegetables, melons and strawberries	4.3	1.6
Flowers and plants	0.2	0.1
Alternate forage	27.4	19.2
Seeds	0.4	0.2
Fallows	7.8	7.1

2. Material and methods

2.1. Study area

The total national land surface of Italy is about 30.2 million hectares. The study area covers ca. 8.1 million hectares, corresponding to the main arable land units as displayed by the CORINE land cover 2006 database (EEA, 2014). According to Eurostat (2014a), the arable land covers about half of the utilised agricultural area (UAA) which totalled 17.3 million hectares in 2012 (9.6% of the European Union UAA) (Table 1). Moreover, it is estimated that about one-third of the Italian agricultural land is located in mountainous areas (4.3 million hectares) while 50.5% is located in areas classifiable as less favorable for agricultural use (6.5 million hectares) (Eurostat, 2014a).

With regard to the environmental conditions, the dominant climates are warm Mediterranean, temperate and subcontinental (Cs and Cf of the Köppen–Geiger climate classification system). Annual precipitation varies from 350 mm year^{-1} in the southern coastal areas of Sardinia and Sicily to 2500–3500 mm year^{-1} in the Carnic Alps region. The national average is about 970 mm year^{-1}. Average annual temperatures range from 5 to 10 °C (typical of the Apennines and Alps highlands) to 14–16 °C (along the southern coasts).

2.2. Approach overview

The overall aim of this study was to conduct a robust modelling of soil loss and carbon stock variation for the Italian arable land using highly spatially-resolved input factors (Fig. 1). Multiple modelling scenarios were performed, in order to quantify the potential past conditions, effects of the Good Agricultural and Environmental Conditions (GAEC) and a possible future increase of the arable land covered by soil conservation practices by 2020.

We should stress that the RUSLE application only estimates the gross erosion. Therefore, the calculated rates may be more reliable to outline the erosion rather than depositional sites. However this approach is fully justifiable because:

1) it is impractical to build a spatially-explicit erosion/deposition model tracking the sediments transport at fine spatial scales for the whole of Italy;
2) environmental concern about erosion is generally low in depositional sites, while it is high at the erosion sites, to which policy is targeted.

2.2.1. The Revised Universal Soil Loss Equation (RUSLE)

The Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) was employed to assess soil erosion losses. Rainfall erosivity and soil erodibility were spatially described by the means of various statistical data and advanced interpolation techniques. The calculations of both factors were carried out using the methods reported in the USLE and RUSLE handbooks (Wischmeier and Smith, 1978; Renard et al., 1997). Topographic conditions and physiographic features of the agricultural lands were derived by the manipulation of a 25 m spatial resolution Digital Terrain Model (DTM) and Landsat imagery. National agricultural statistics were used to spatially describe the variations of land cover and management at NUTS-3 level (Nomenclature of Territorial Units for Statistics; Eurostat, (2015). The P-factor values (support practices) were designed according to the data reported in the European Agricultural Census 2010 (NUTS-2 level) (Eurostat, 2014b) and the compulsory standards introduced by the Good Agricultural and Environmental Conditions (GAEC) (MARS, 2014). A detailed methodology description is reported in the Supplementary materials.

2.2.2. CENTURY agroecosystem model

CENTURY is a process-based model designed to simulate carbon (C) and nitrogen (N) dynamics in natural or cultivated systems, using a monthly time step. The soil organic matter sub-model includes three SOC pools, namely active, slow and passive, along with two fresh residue pools, structural and metabolic, each with a different decomposition rate. Soil temperature and moisture, soil texture and cultivation practices act as modifying factors on potential decomposition rate constants. The model is also able to simulate the soil water balance, using a weekly time step, while a suite of simple plant growth models are included to simulate carbon and nitrogen dynamics of crops, grasses and trees. The model was recently integrated in a computational platform to estimate the SOC stock at European level (Lugato et al., 2014a) and simulate alternative scenarios of land use and management impacts on SOC in agricultural soils (Lugato et al., 2014b; Lugato and Jones, 2015). More details on the modelling architecture and the numerical and spatial layer inputs used are provided in the supplementary materials.

The CENTURY model does not directly estimate the soil loss by erosion, but specifying erosion rates as an input allows the model to account for the lateral carbon fluxes associated with sediment transport (Fig 1). While the SOC budget is calculated for the fixed depth 0–30 cm, it is possible to specify: (1) the enrichment factor of carbon leaving the soil profile by sediments (i.e., the ratio between the carbon concentration in sediments and in the soil profile) and; (2) the quality and the amount of the carbon in deeper soil layers that are ‘moved up’ into the top 30 cm soil layer (in case of net erosion; sources) or deposited (sinks).

Since the RUSLE provides only the gross erosion, two consequential assumptions were made in the simulations. Firstly, the enrichment factor was set to 1.2 considering that SOC stratification is limited in arable soils that are commonly ploughed in Italy (Blanco-Moure et al., 2013). Second, the incoming SOC pool from the deeper layers was assumed to be more recalcitrant than in the top soils (Kirkels et al., 2014) and composed as the following proportion of the 0–30 profile SOC pools: active *0.2 + slow * 0.4 + passive * 0.8.

This approach may produce a small bias in depositional areas where the carbon in sediments may be enriched relative to the average of the soil profile; nevertheless, it is justified by the lack of information to delineate those areas at national scale as well as the lack of data on the concentration of carbon in transported soil.

2.3. Potential impact of GAEC application

The following scenarios were simulated to assess the impact of GAEC application on soil erosion and SOC conservation:

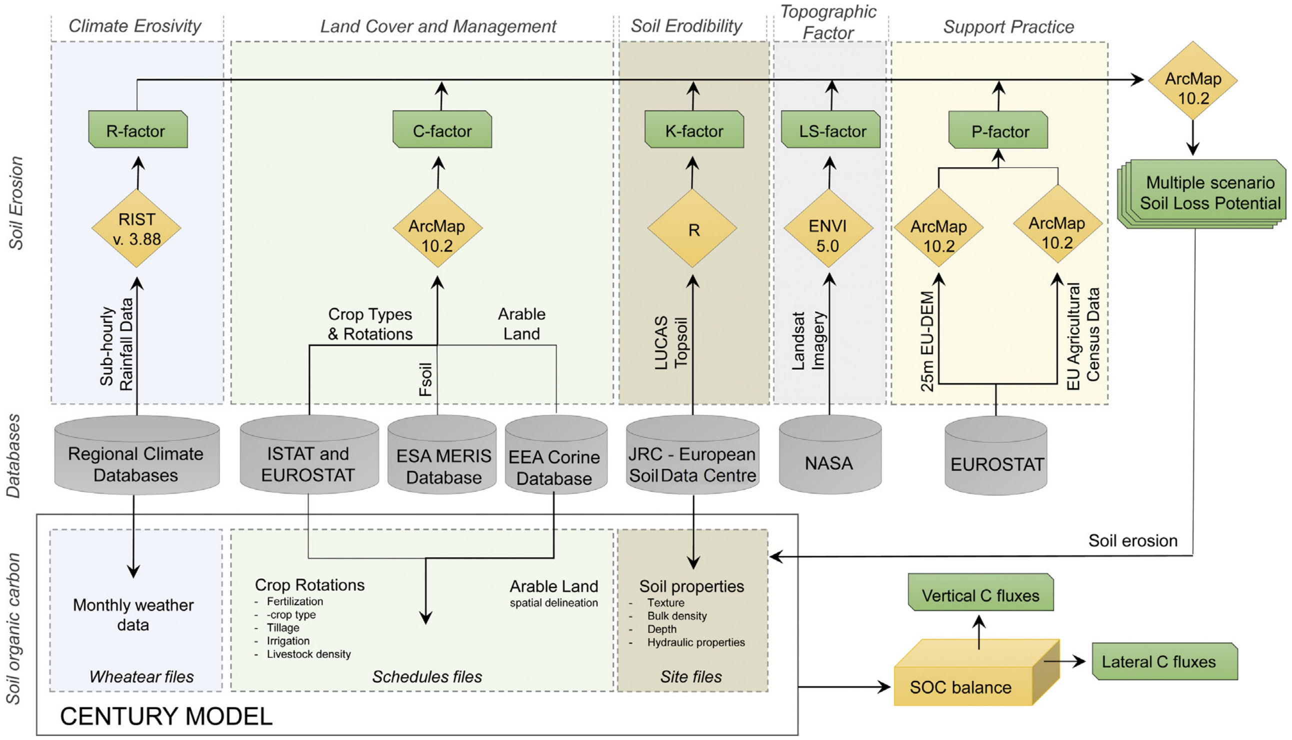


Fig. 1. Workflow—Assessment of soil loss and carbon stock variation for the Italian arable land.

a) 'Baseline': In order to estimate the impact of GAEC implementation, a 'baseline scenario' underlying the absence of any specific policy on erosion prevention and carbon conservation was simulated; chronologically, it refers to the conditions before cross-compliance introduction (2003). For the erosion model, this scenario involved the calculation of a pre-GAEC C-factor based on crop statistics (Table 1 bis, Supplementary material), while the P-factor was assumed to be constant for the whole study area (equal to 1, i.e., no erosion prevention practices according to Wischmeier and Smith, 1978). The soil erosion rates were then inserted into the 'baseline scenario' simulated with CENTURY, which is highly consistent with the erosion model since, crop rotation schemes and management were derived from the same databases.

b) 'Current': This scenario is based on the implementation of the compulsory GAEC standards. The data of the European Agricultural Census (year 2010) are employed to define the specific conservation practices and their application areas on the arable land (Fig. 2). Based on this information, the C and P factors were recalculated (Supplementary material) to estimate the soil erosion after GAEC implementation. The new soil erosion rates were introduced into the CENTURY model and the rotations were modified according to the compulsory standards indicated by GAEC. In particular, crop residues were maintained in the field during the winter period, the rate of straw exportation was reduced from 50 to 30% and cover crops were inserted after summer crops. Since, there are no annual statistics on the areal coverage of GAEC application, the 'current' scenario was started for the year 2005 (year of implementation of GAEC by Member States, Angileri et al., 2011; Panagos et al., 2015b) maintaining a constant area coverage as in 2010.

c) 'Technical potential': This scenario suggests the technical biophysical capacity of the arable land to sequester SOC, when GAEC standards are applied to the entire surface for a long-term period (2050).

The SOC change under GAEC implementations was assessed as a difference between the 'current' and 'baseline scenario', both projected to 2014: for the 'potential' scenario the difference to the 'baseline scenario' was calculated until 2050. This means that GAEC effects were evaluated according to a consequential approach used to evaluate alternative policies.

3. Results

3.1. Soil erosion

Fig. 3 shows the soil loss potential predicted for the 'baseline scenario' and the variations ascribable to the implementation of compulsory standards introduced by the Good Agricultural and Environmental Conditions (GAEC), at present and in a conservative scenario.

The annual average soil loss predicted by RUSLE for the 'baseline scenario' totals 67.59×10^6 Mg year^{-1} with an average area-specific soil loss potential of 8.33 Mg ha^{-1} year^{-1} (Fig. 3(a)). The average soil surface level change totals 0.065 mm year^{-1} (bulk density values obtained by Ballabio et al., 2015) with a long-term average change of 19.4 mm (over 30 years). During this period the application of conservation practices was not mandatory. The high soil erosion rates reflect the heterogeneity and propensity of the landscape to erosion, where locally the annual average rainfall erosivity can be as high as 6200 MJ mm ha^{-1} h^{-1} year^{-1} ($\sigma = 1558$ MJ mm ha^{-1} h^{-1} year^{-1}) and the slopes on cultivated land can exceed the 15% (13.9% of the study area). The NUTS-3 weighted C-factor also had a significant spatial influence ranging from 0.167 to 0.297 ($\bar{x} = 0.212$, $\sigma = 0.025$). The results show that about 10 and 30% of the study area are classified by very low and low erosion rates (classes 1 and 2), respectively. Large portions of land characterized by these classes are noticeable on the Apulian plateau, in the Po Valley, along the Tyrrhenian coast, and in the Western Sardinia and the Apennine intermontane plains. Here, the agricultural activities are mostly carried out on flat alluvial and structural plains

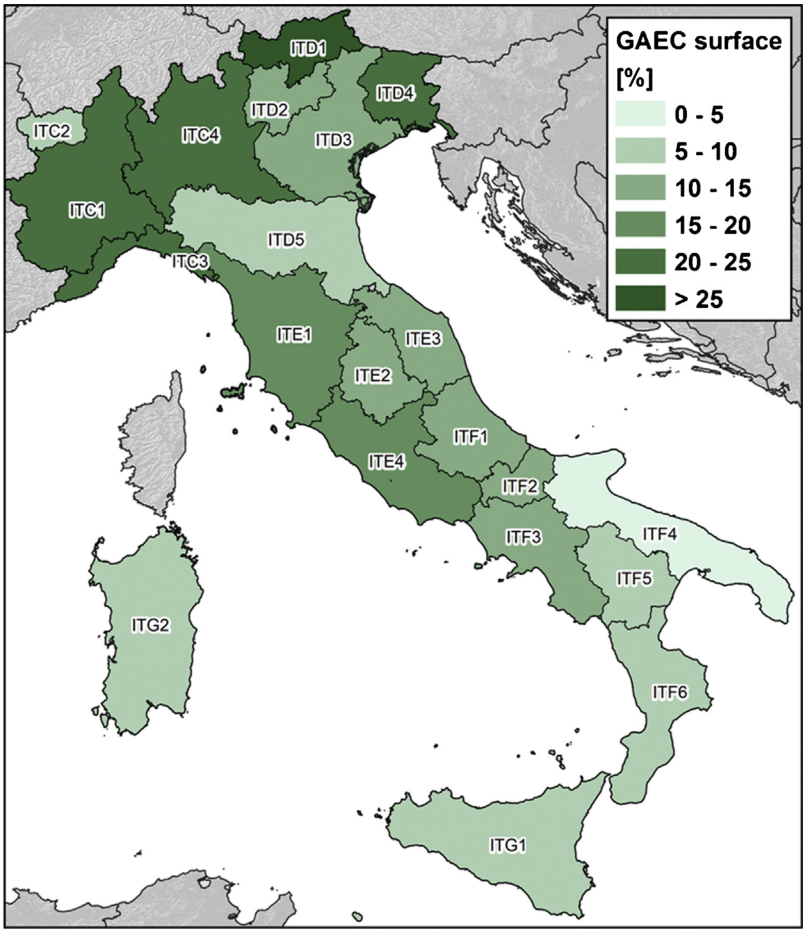


Fig. 2. Relative area of GAEC application on the arable land at NUTS2 level.

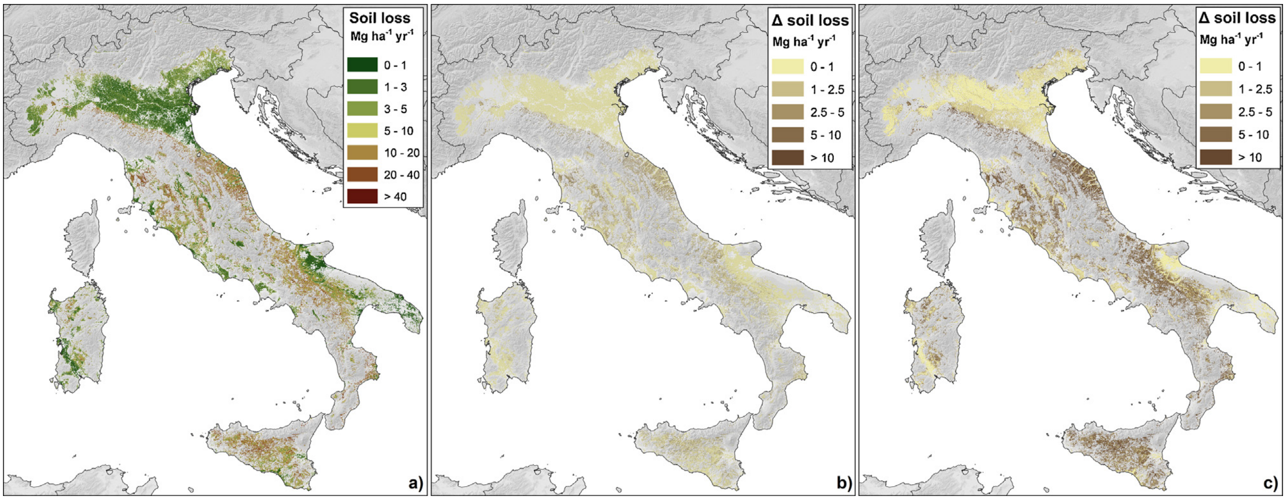


Fig. 3. (a) Shows the average annual soil loss potential in the Italian arable land for the baseline scenario; (b) and (c) show the soil loss variations calculated by modelling the potential effect of current GAEC conditions and the technical potential scenario, respectively.

with a low average slope (ca. 1.6%). Moderate (class 3) and high (class 4) erosion values are simulated for 15.4% and 16.5% of the study area, respectively. These soil loss classes typically occur in hilly areas of transition towards the Apennine regions (slope average = 4.2%) and where the rain hits the ground with high energy (e.g., Friuli Venezia Giulia (ITH4), such as in Liguria (ITC3) and Campania (ITF3)). The rest of the area (29.2%) (classes 5–7) exceeds the tolerable soil loss threshold (T) formulated for Mediterranean environments (10 Mg ha^{-1} year^{-1} Morgan, 1995); in areas where these soil loss classes dominate a progressive decrease of the ability of soils to sustain vegetation and livestock is noticeable. These severe erosion forms are primarily located along the Apennines and the surrounding hilly areas, affecting in particular Liguria (ITC3), Calabria (ITF6) and Tuscany (ITI1).

The ‘current scenario’ provides information on the present soil loss conditions, which reflects the consequence of the adoption of soil conservation practices as defined in the present cross compliance strategy and the European Agricultural Census of 2010. From the modelling prospective, the compulsory standards proposed within the GAEC regulation prove to be somewhat effective in reducing soil erosion (Fig. 3(b)). At the national level, the decline of soil loss potential totals 10.8%. The current average area-specific soil loss is 7.43 Mg ha^{-1} year^{-1}, totaling a potential loss of 60.28 × 10^6 Mg year^{-1}. Geographically, the GAEC design leads to a situation that indicates for the most of the central and northern Italian provinces a reduction of soil loss above the national average. The NUTS-3 showing the highest GAEC effect were Bolzano (21.5%), L'Aquila (20.7%), Savona (20.5%), and with a lesser extent Imperia (20%), Genova (19%) and Massa Carrara (17.1%). Less favorable effects are generally noticeable in the southern regions such as Foggia (6.1%), Lecce (4.9%) and Brindisi (4.9%), and for the major islands. With the introduction of GAEC, about 93.3% of the cropland areas experience a reduction of soil erosion smaller than five percentage points, while about 25% of the cropland areas, equal to 2.08 million hectares, were still predicted to experience soil loss exceeding the T threshold.

Fig. 3(c) shows the variation on the soil erosion potential for the proposed 'conservative scenario', i.e., 'technical potential'. In this exercise we kept the R-, K- and LS-factor constant, while the C- and the P-factor were modified. The 'technical potential' results in a conservative soil management scenario by (i) introducing contour farming for the arable land on slopes greater than 10% and (ii) applying the GAEC standards to the entire modeled land surface. The annual average soil loss is 33.1 × 10^6 Mg ha^{-1} year^{-1}, with an average area-specific soil loss potential of 4.1 Mg ha^{-1} year^{-1}. The overall soil loss reduction compared to the 'baseline scenario' is equal to 51% (34.5 × 10^6 Mg ha^{-1} year^{-1}). Compared to the 'current scenario', the 'conservative scenario' shows a further decrease of the soil loss potential equal to 42.8%. Very low and low soil erosion rates are predicted for 20.7% and 41.3% of the study area, respectively. The cropland areas experiencing soil erosion potential above the *T* values are reduced to 0.82 million hectares (10.2% of the arable land surface). The long-term soil surface level change totals 9.5 mm (30 years).

Fig. 4 shows the modelling results for two localities in Tuscany notoriously prone to soil erosion processes. The image offers tangible examples of the modelling outcomes and their ability to predict soil erosion patterns.

3.2. *Soil organic carbon*

The average carbon losses through erosion in the 'baseline scenario' period are reported in Fig. 5(a). The map clearly depicts very small losses in the main plains (Po Valley and Tavoliere delle Puglie located in northern and southern-east Italy, respectively) with values <0.05 Mg C ha^{-1} year^{-1}. In the sloping areas the carbon erosion rates range between 0.1 and 0.3 Mg C ha^{-1} year^{-1} with some peaks along the Apennine dorsal. Overall, the data distribution shows a median loss of 0.11 Mg C ha^{-1} year^{-1} with the 1th and 3rd quantiles equal to 0.05 and 0.2 Mg C ha^{-1} year^{-1}, respectively.

The potential impact of GAEC application on eroded carbon is illustrated in Fig. 5(b), which depicts the prevented eroded carbon (negative values) in the average hectare according to the proportion of GAEC applied. As expected, the potential impact is minimal in the flat areas (<−0.004 Mg C ha^{-1} year^{-1}), while generally between −0.009 and −0.030 Mg C ha^{-1} year^{-1} in sloping areas. Considering the arable land covered by GAEC standards (1.42 on 8.01 Mha of arable land), the cumulated difference of eroded carbon is −0.034 Mt year^{-1} over the whole territory.

The soil organic carbon stock in the top soils (0–30 cm) simulated in the 'baseline scenario' is reported in Fig. 5(c). The SOC distribution varies widely depending on the pedo-climatic and agricultural systems, with a median value of 42.2 Mg C ha^{-1} and the 1st and 3rd quantiles of 31.1 and 53.1 Mg C ha^{-1}. At national level, the arable soils are estimated to contain 351.4 Mt of C stock.

The potential impact of GAEC application considering both the lateral (erosion) and vertical fluxes (carbon input and soil respiration) is depicted in Fig. 5(d), which shows the SOC accumulated in the average hectare according to the proportion of GAEC applied. The median SOC gain totals 0.02 Mg C ha^{-1} year^{-1} with the highest accumulation rates in north-western Italy and the lowest in the Puglia and Calabria regions (southern part). In the north-eastern part where 20–25% of arable land is covered by conservative management practices, the SOC accumulation is more than 0.06 t C ha^{-1} year^{-1}. The SOC changes are in general consistently driven by the proportion of land covered by GAEC standards (Fig. 2), which is higher in the Piedmont (ITC1) and Lombardy (ITC4) regions while generally lower in southern Italy.

Some hotspot areas in the northern Apennine are characterized by high soil erosion rates (Fig. 3). For these regions the model simulated high SOC sequestration rates likely driven by the reduction of carbon lateral fluxes. Considering the overall arable land covered by GAEC standards, the model simulated an average cumulated SOC gain of 0.2 Mt year^{-1} since 2005. The prevented eroded carbon contributed of about 17% to the total SOC accumulation. At regional level (NUTS2), the mitigation potential of GAEC showed dependencies on both, biophysical conditions and the arable area subjected to GAEC application. The highest SOC gains were simulated for northern Italy (Piedmont (ITC1) and Lombardy (ITC4)), followed by Sicilia where straw management is a key factor affecting SOC balance due to the extensive presence of winter cereals. In the mountain regions (Trentino, Alto Adige (ITH1–ITH2) and Liguria (ITC3)) despite the altogether small agricultural area, the prevented erosion contributed significantly (>70%) to SOC accumulation (Fig. 6).

Applying the 'technical potential' scenario, involving the application of GAEC standards to the whole arable land, the annual rates of SOC accumulation are almost three time higher than those of the 'current scenario' (Fig. 7). In particular, the geographical patterns of SOC change are more closely related to the areas with the highest soil erosion rates (Fig. 3(a)) and rate changes after GAEC application (Fig. 3(c)), with values >0.15 Mg C ha^{-1} year^{-1} along the Apennine and in the two main islands. Soils in northeastern Italy show a lower accumulation capacity. In a long-term perspective (2050), the cumulated potential SOC gain is estimated to reach almost 40 Mt C, corresponding to 0.93 Mt year^{-1}.

4. Discussion

4.1. *Soil loss*

The scenario-based analysis presented in this study was designed to support national as well European decision-makers to identify the areas experiencing soil erosion, to understand the magnitude of natural constricting forces and to evaluate the effects of the current effort applied to control erosion and protect the natural resources.

It is well-known that soil erosion is an important national issue in Italy (Torri et al., 2006; Costantini and Lorenzetti, 2013; Panagos et al., 2015c,d). Previous studies carried out along the Peninsula indicate that most, if not all, agricultural cropland areas experience some degree of soil erosion by water. However, studies covering smaller areas, heterogeneously distributed across the Italian cropland areas provide an incomplete and spatially inconsistent picture at the national scale. The harmonized datasets and the consistency of the methodology employed to achieve the cropland soil erosion map of Italy, besides improving model performance, contribute

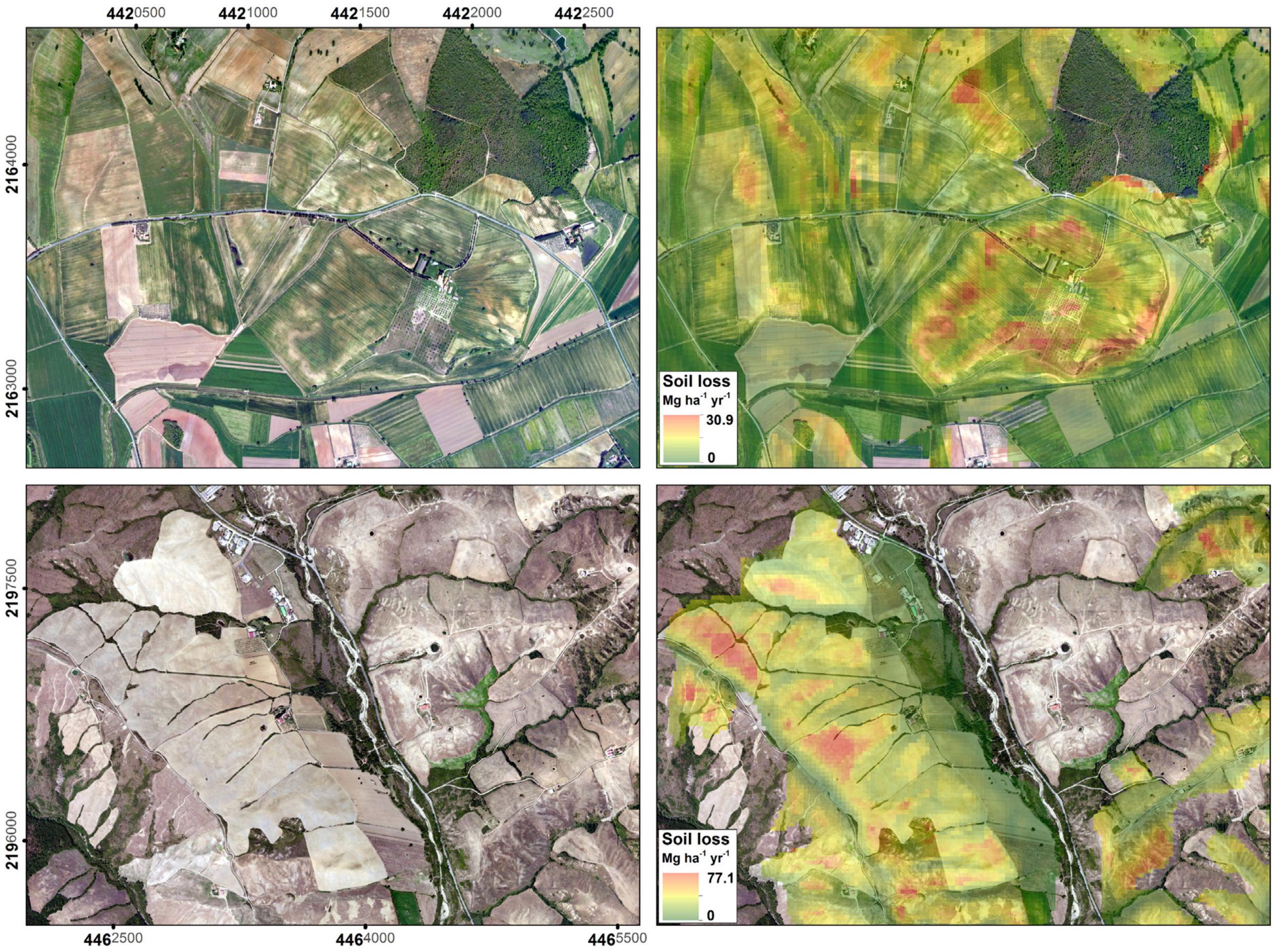


Fig. 4. Example of the outcomes of the RUSLE's model application in the Southern Tuscany. The upper images show hilly arable lands ongoing soil erosion and degradation processes (Magliano: 2163500E 4421500N). The images below show farming activities among calanchi landforms (Radicofani: 2196000E 4464000N).

to fill this gap and to offer a tool capable of supporting local and regional planning initiatives. With a spatial resolution of 25 m^2, the modelling outcomes are comparable with those generally obtained by the application of the RUSLE model in experimental catchments (ranging from 20 to 40 m, Amore et al., 2004; Candela et al., 2006; Märker et al., 2008; Terranova et al., 2009; among others). Fig. 8 reports a comparison between the results of this study with previous large scale modelling approaches proposed by the European Soil Bureau (Kirkby et al., 2003; van der Knijff et al., 2000; Bosco, personal communication). It shows tangible graphical indications about the important step forward made on large-scale soil erosion modelling, highlighting the importance of the spatial resolution, in order to correctly represent the influence of the topography on the erosion process (Bryan, 2000) and accurately locate the slopes which are potentially prone to severe erosion processes.

For the first time after the introduction of the cross-compliance mechanism in 2003 (CAP), the environmental effect of GAEC applications on erosion and carbon budgets were studied. The 'baseline scenario', with an average area-specific soil loss potential of 8.33 Mg ha^{-1} $year^{-1}$, confirms Italy as being among the countries with the highest soil erosion rates in Europe (Panagos et al., 2014b). From the modelling aspect, the introduction of the Good Agricultural and Environmental Conditions ('current scenario') in 2003 had a positive impact, effectively reducing soil loss by an estimated 10.8% (average area-specific soil loss, 7.43 Mg ha^{-1} $year^{-1}$). It is estimated that 8.5% of the soil loss reduction is attributable to the application of conservative tillage practices and winter cover crop whereas the remaining 2.2% is due to the quasi-contour farming. However, the post-GAEC modelling results remain considerably higher than the European average value derived by plot measurements (4.4 Mg ha^{-1} $year^{-1}$; σ 12.15 Mg ha^{-1} $year^{-1}$; Cerdan et al., 2010). This situation reflects the high susceptibility of the Italian landscape to erosion, where: (i) the erosive power of rainfall falling on the cropland is 2.4 times higher than the European average (650 MJ mm ha^{-1} h^{-1} $year^{-1}$; Panagos et al., 2015a), (ii) the farms lying on hilly (>200 <600 m a.s.l.) and mountain (>600 m a.s.l.) areas cover about 39.4% of cropland, and (iii) about 25% of the study areas is located on slopes greater than 10%. It is interesting to note that while Italian cropland shows the highest soil erosion risk in Europe most conservation soil erosion practices are not applied (Angileri et al., 2011). Winter cover crop, reduced tillage and no-till farming involves only 15.6, 5.5, and 5% of the Italian cropland, respectively. With the exception of no-till farming (EU average 4%), the Italian values are noticeably below the European averages of 19% for winter cover crop and 21.5% for reduced tillage (Eurostat, 2014b).

It is well-known that the soil erosion is a spatially varying process (Wischmeier et al., 1971; Morgan, 2009). According to the 'baseline scenario' about 73% of the erosion processes occur over 25% of the Italian cropland. The farms most exposed to soil erosion are the ones located in less favorable agricultural lands (slopes greater than 10%), which experience ca. 64% of the total soil loss predicted annually. With the introduction of the GAEC, the soil erosion potential in these areas decreases from 21.2 to 18.9 Mg ha^{-1} $year^{-1}$ (−10.4%). A slightly decrease if we consider that the predicted soil

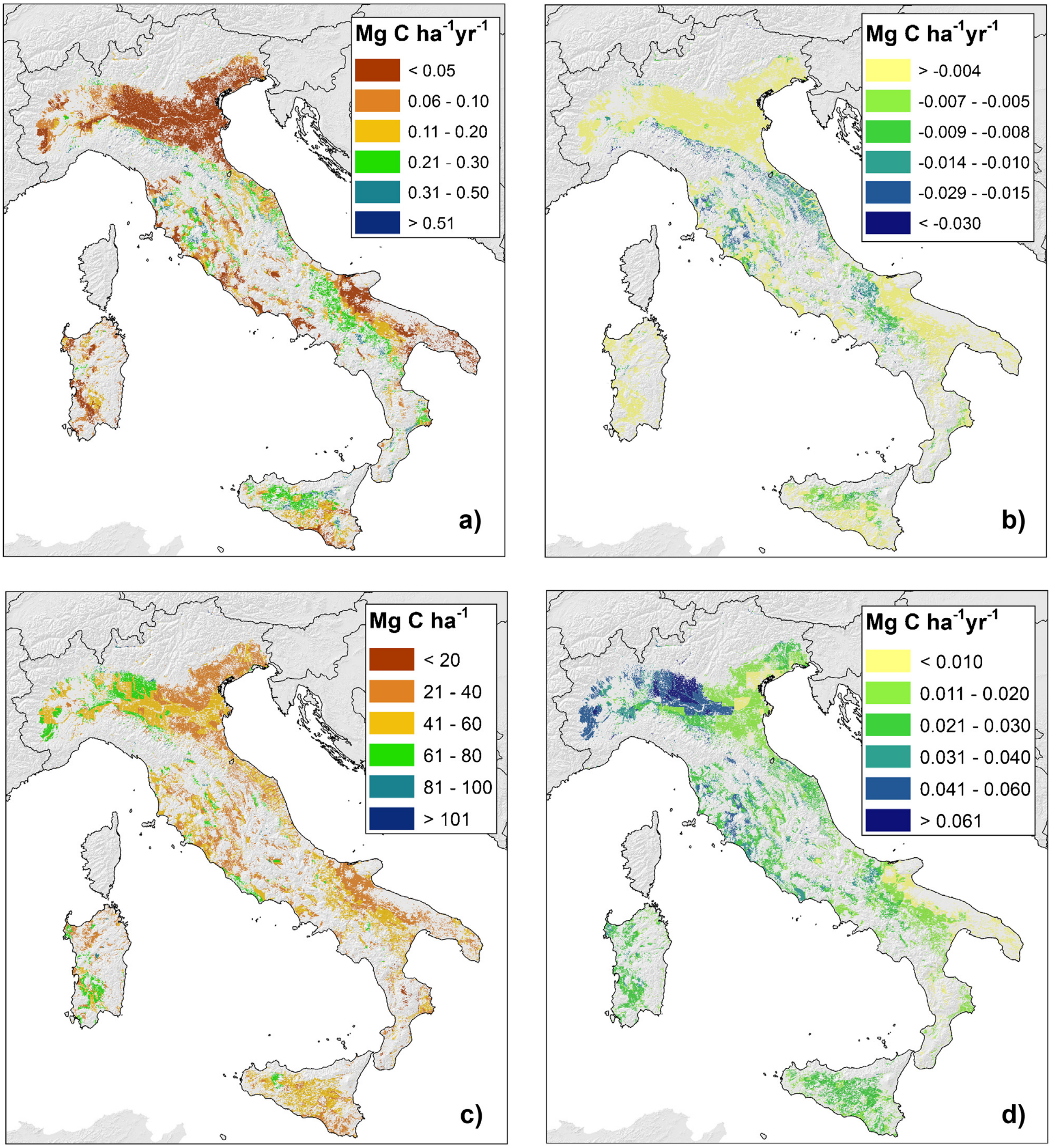


Fig. 5. (a) Organic carbon lost by erosion (lateral flux) in the baseline scenario; (b) avoided eroded C with GAEC application; (c) soil organic carbon stock (0–30 cm layer) in the baseline scenario; (d) soil organic carbon accumulation due to GAEC application.

erosion rates are still about twice the tolerable soil loss threshold (T) formulated for Mediterranean environments (10 Mg ha^{-1} year^{-1} Morgan, 1995). If the 'current scenario' soil loss rates are close to the predicted values, sizable sectors of the Italian croplands could already suffer from decreasing fertility (Morgan, 2009). Despite this the GAEC standards for Italy lack specific requirements for these lands. For sloping cultivated land in Italy, the GAEC requires the annual construction of furrows for the collection of runoff water. However, such practice is compulsory only if the farmers notice evidence of soil erosion on their land. Unlike other European countries experiencing high erosion rates (Spain, Romania, Belgium, Greece, Malta, and Cyprus) (Angileri et al., 2011), contour farming was not included as mandatory standard. Contour farming may be a conservation practice which is rather effective in reducing soil erosion in hillslope farming (Kirkby and Morgan, 1980), and according to our modelling may be able to bring a further decrease of soil loss for the less favorable agricultural lands estimated in 5.6 Mg ha^{-1} year^{-1} (from 18.9 to 13.3 Mg ha^{-1} year^{-1}; −29.6%).

Moreover, although the improvements resulting from the introduction of the GAEC standards have the potential to noticeably reduce soil loss rates, the regional statistics revealed a heterogeneous scenario. The soil loss rates reduction ranges from 5.1%

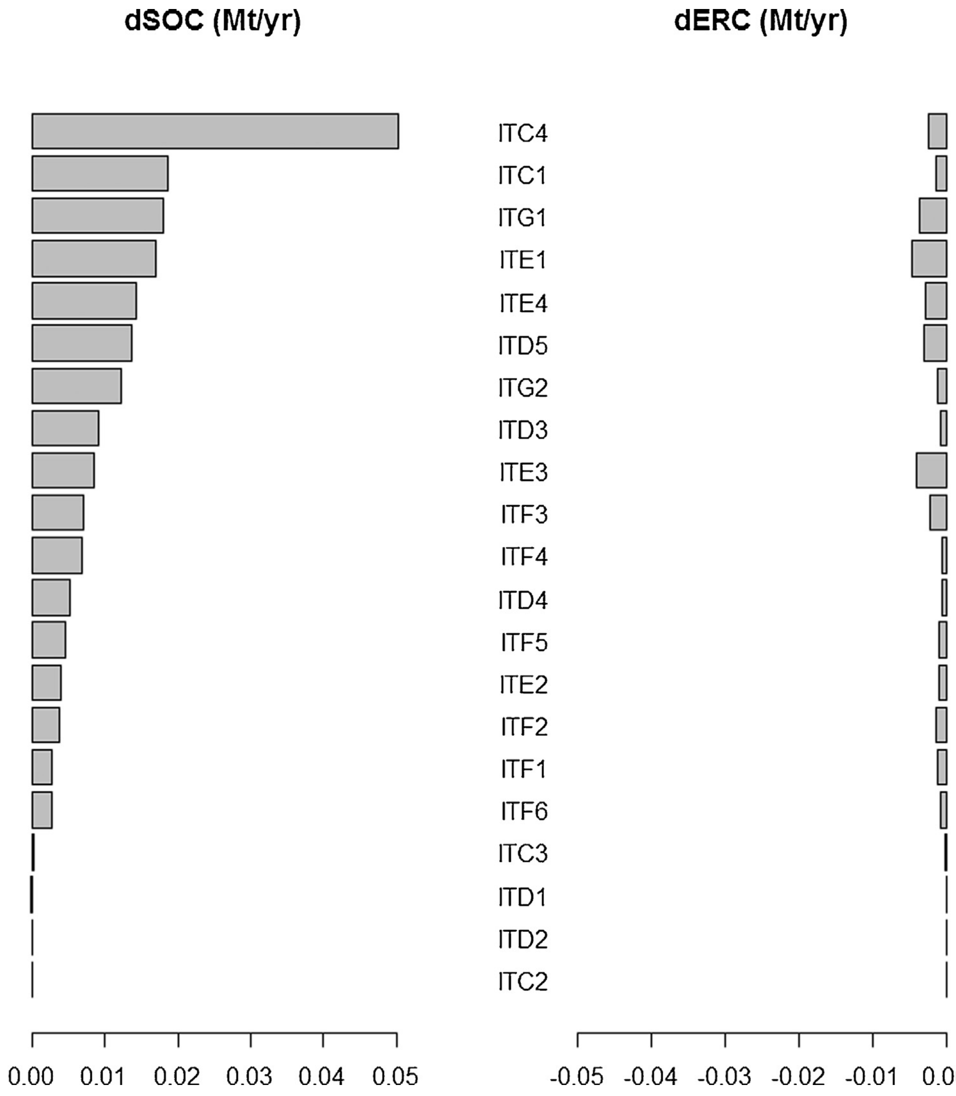


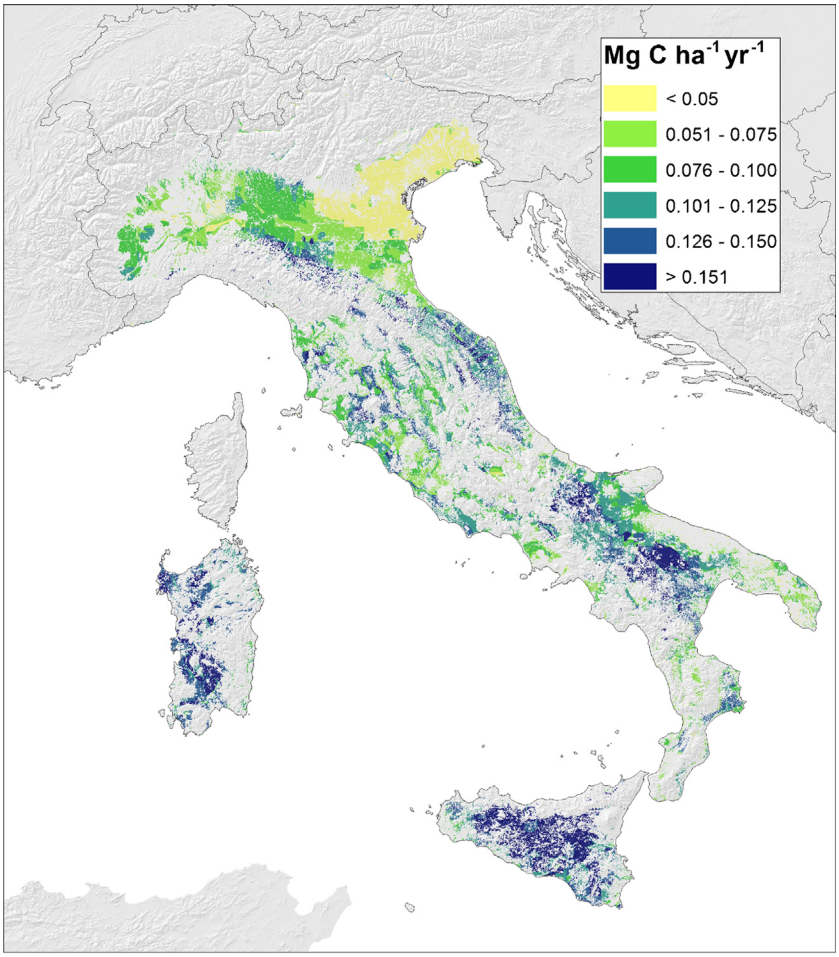
Fig. 6. Cumulated soil organic carbon gained by GAEC application (left) and avoided eroded carbon (lateral flux) at NUTS2 region. (NUTS-2 codes: ITC1—Piedmont; ITC2—Valle d'Aosta; ITC3—Liguria; ITC4—Lombardy; ITD1 & ITD2—Trentino-Alto Adige; ITD3—Veneto; ITD4—Friuli-Venezia Giulia; ITD5 —Emilia-Romagna; ITE1—Toscana; ITE2—Umbria, ITE3—Marche; ITE4—Lazio; ITF1—Abruzzo; ITF2—Molise; ITF3—Campania; ITF4—Puglia; ITF5—Basilicata; ITF6—Calabria; ITG1—Sicily; ITG2 —Sardinia).

(Apulia, ITF4) to 20.7% (Trentino–Alto Adige, ITH1–ITH2) (Fig. 9). In this respect, we proposed the so called 'technical potential' scenario, with the aims to explore the potential effects of the implementation of a fully conservation agriculture system based on the improvement and harmonization of the GAEC standards across the Italian cropland. This modelling exercise shows a considerable soil loss reduction potential (ca. −45% with respect to the 'current scenario'), with relevant effects on the land capacity to sequester SOC. With regard to the less favorable Italian agricultural lands, it was estimated that the combined effect of contour farming, water collection furrows, winter cover crop and reduced tillage ('technical potential' scenario) may reduce soil loss rates close to the tolerable soil loss threshold (T), of 10.5 Mg ha^{-1} year^{-1} (−50.5% with respect to the 'baseline scenario').

At regional level, the findings are in line with the scenario described in academic literature (Ventura et al., 2004; Torri et al., 2006; Märker et al., 2008; Terranova et al., 2009; Costantini and Lorenzetti, 2013; Bagarello et al., 2015). Soil loss is higher in Sicilia (ITG1), Marche (ITI3), Toscana (ITI1) and Emilia-Romagna (ITH5) (Fig. 9). The analysis of the influence of the different factors triggering soil loss at NUTS-2 level shows the topographical factor (LS) playing a primary role (±805%), followed by the rainfall erosivity (±268%) and the soil erodibility (±79%). With regard to the cover and management factor, a significant but lower spatial variation (±29%) was observed ('baseline scenario'), with values ranging from 0.187 (Calabria, ITF6) to 0.241 (Trentino–Alto Adige, ITH1-ITH2) (national $\bar{x} = 0.212$, $\sigma = 0.014$).

4.2. Soil organic carbon

Some of the standards indicated by GAEC to reduce erosion, such as residue cover maintenance, reduced tillage intensity or the use of cover crops are generally recognized to increase the SOC stock. Many long-term experiments have investigated the effect of these management practices on C sequestration (West and Post, 2002), although few model applications have tried to quantify their effect at large-scale (Smith et al., 2005; Lugato et al., 2014a). In particular, some attempts were made coupling erosion/transport and SOC models of different complexity (Van Oost et al., 2005a,b), but the scale was generally limited to the basin level. Yadav and Malanson (2009), for instance, previously used the CENTURY model in combination with the GeoWEPP erosion/transport model for a small basin in Illinois (25 ha). In this study, despite depositional areas were identified, still the assumption of 40% loss of SOC in sediments



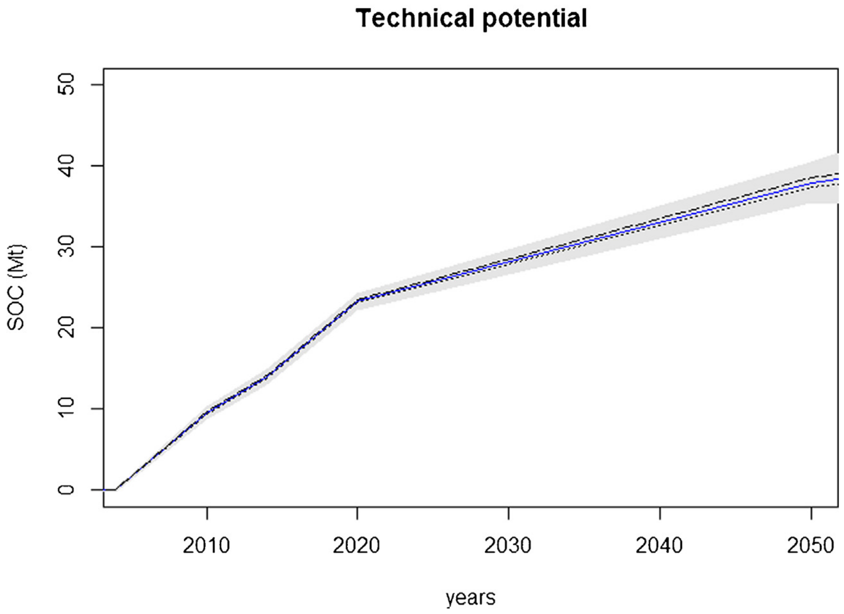


Fig. 7. Soil organic carbon accumulation rates (Mg C ha^{-1} year^{-1}) under the full application of GAEC standard in arable lands (technical potential scenario) (above) and cumulated values (Mt) by 2050 (below).

during transportation is made. The rate of oxidation of SOC exposed during transportation and deposition is still a big source of uncertainty (Kirkels et al., 2014). Additionally, uncertain remains as to whether deposited sediment is subject to deep burial or remains in an exposed soil surface condition (Quinton et al., 2010). Conversely in the eroding areas (source areas) the coupled RUSLE–CENTURY model can take the lateral carbon losses, the dynamic replacement (i.e., the effect of incoming net primary production on the SOC

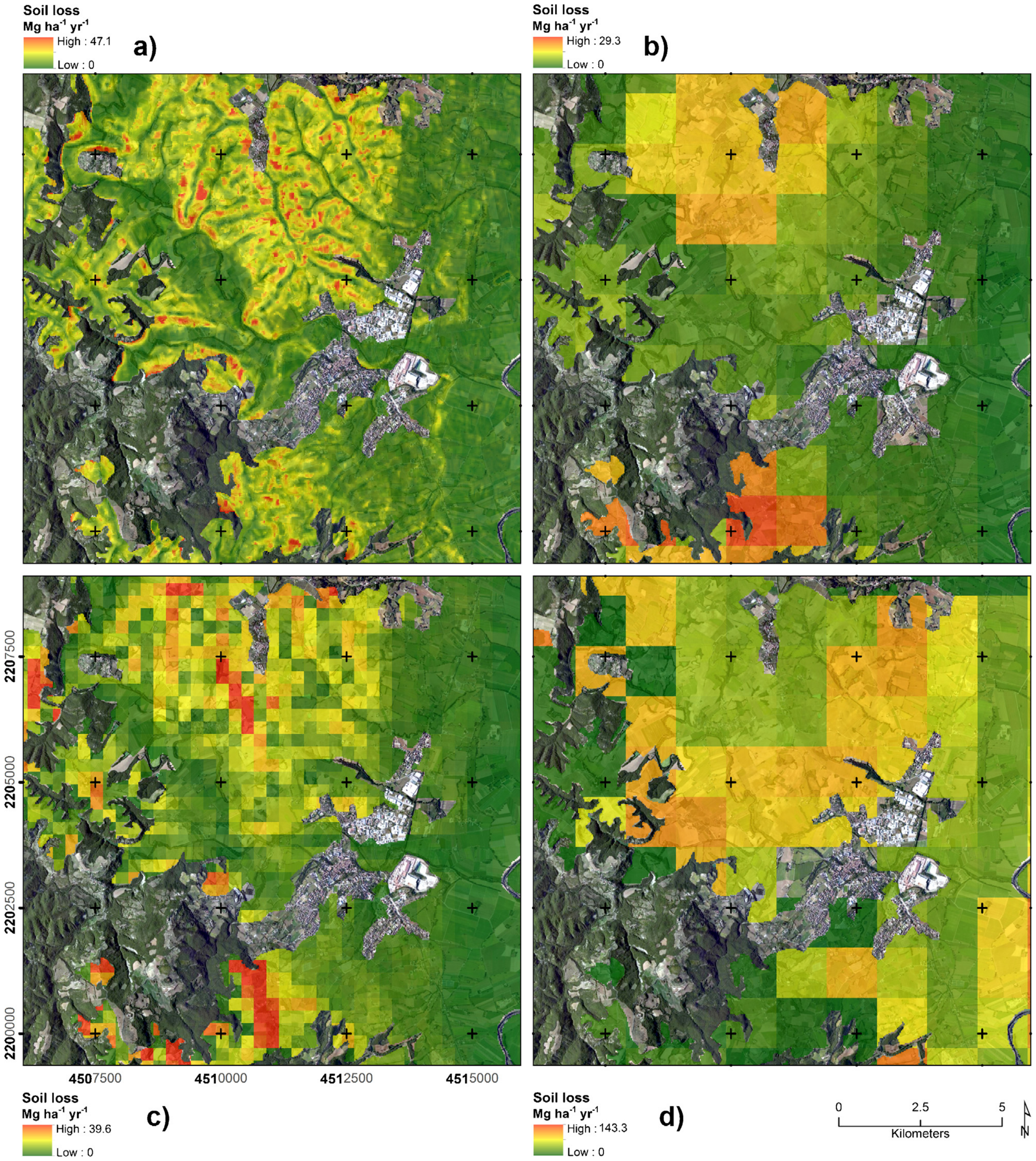


Fig. 8. Comparison between the latest modelling outcomes carried out by the European Soil Bureau about soil erosion. (a) 25 m baseline scenario presented in this study. (b) 1000 m modelling presented by Bosco, personal communication. c) 250 m modelling proposed by Grimm et al. (2001). (d) 1000, modelling proposed by Kirkby et al. (2003).

depleted topsoil) and the quality of the incoming carbon from the deeper layers on SOC turnover into account. Using a coupled SOC and spatially distributed soil erosion model for a region in central Belgium, Nadeu et al. (2015) highlight the role of conservation practices on SOC sequestration. The authors state that soil management practices targeting C sequestration can be most effective when soil erosion is reduced given that erosion loss can reduce potential C uptake by plants, particularly in sloping areas.

Our results indicate that 17% of SOC gains due to GAEC application may be attributable to reduced erosion, underlying the necessity to include this process in accounting for SOC changes. We have to point out that some bias on SOC balance may be present in depositional sites (sink areas) that are not delineated by the RUSLE approach, providing only the net soil erosion. However, this study does not investigate the overall landscape carbon balance but, being limited to arable soils, aims to highlight the magnitude and the direction of changes of erosion and SOC fluxes under the implemented policies. It is likely that depositional areas under the agricultural land use are less prone to degradation since they

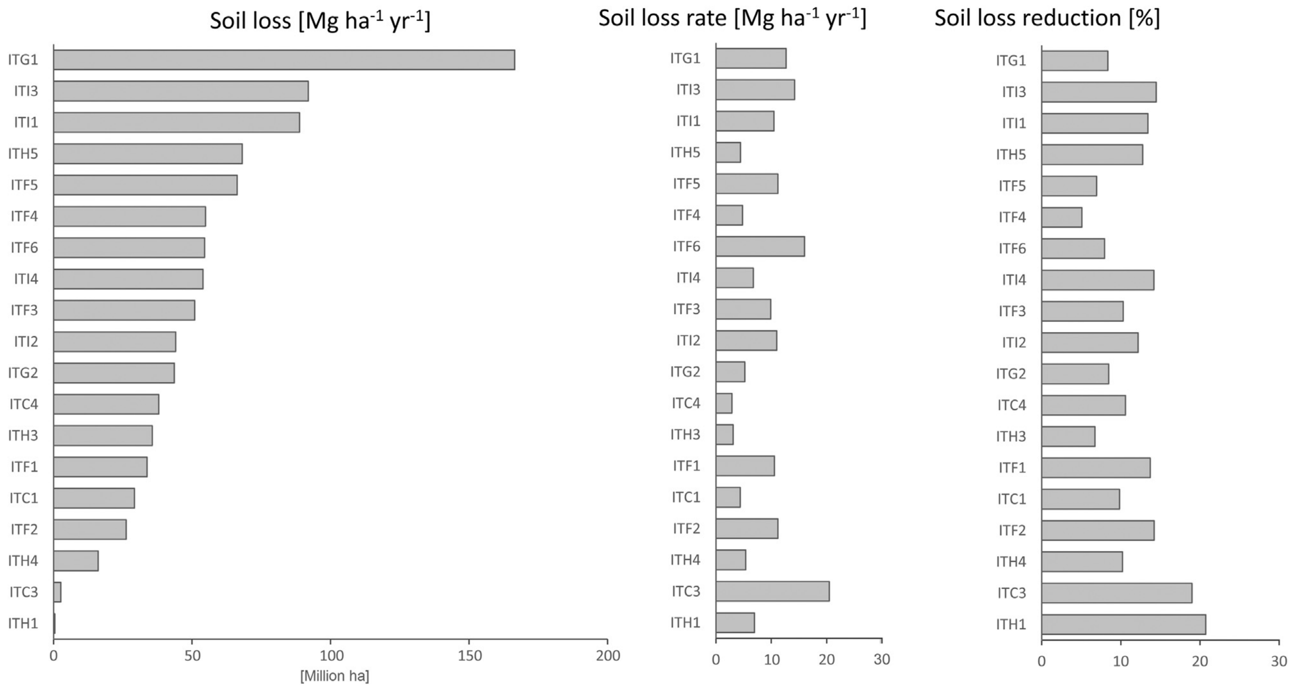


Fig. 9. Descriptive statistics of soil loss for Italian regions (NUTS-2). (a) Annual average soil loss predicted for the ‘baseline scenario’. (b) Average area-specific soil loss potential predicted for the ‘baseline scenario’. (c) Potential decrease in soil loss due to the adoption of the GAEC conservation practices (NUTS-2 codes, see Fig. 6).

likely received sediments enriched in nutrients, thus fostering plant growth.

The capacity of arable soils to store SOC is on average three times higher than the ‘current scenario’ under the technical potential scenario. Lugato et al. (2014b) estimates the technical potential of different conservative management practices but excluding erosion processes. As a consequence, the territorial patterns of SOC changes are strongly dependent on the different management practices applied. In this study the inclusion of carbon lateral fluxes highlights the importance to reduce the soil losses, as the highest beneficial effect in term of SOC gains are estimated for the areas strongly exposed to soil erosion processes. Moreover, the full application of GAEC standards to the entire Italian arable land gives rise to expectations reaching a potential SOC accumulation of 38 Mt year^{-1} by 2050, equal to about 7.8% of the total GHG national emission (EEA).

5. Conclusions

After the introduction of the cross-compliance mechanism, many efforts have been made in the EU to increase the sustainability of agricultural systems. So far, the monitoring of the implementation of GAEC standards is limited to the verification of their application by ground-based surveys or remote sensing techniques. However, what is still largely unknown are the actual effects on processes affecting soils such as erosion and SOC change, which ultimately determine the efficacy and cost-effectiveness of the policy. The cost of monitoring such changes appears economically unsustainable at farm system level due to the number of subjects involved. In this context, the use of a well-calibrated model may become a diagnostic tool to quantitatively assess the policy impact. Our results obtained by coupling the high resolution RUSLE with an ecosystem biogeochemical model clearly indicate that higher residues restitution, increased soil cover and lower tillage disturbance may both reduce the erosion and increase the soils’ SOC contents.

Consequently, these estimates provide a useful starting point for scientists and decision-makers but further efforts should be made to link biogeochemical and geomorphological process occurring at landscape level into a regional, continental or global framework.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landusepol.2015.09.033

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