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Catena 68 (2006) 194 – 199
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The cost of soil erosion in vineyard fields in the Penedès–Anoia Region (NE Spain)

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Abstract

On-site and off-site environmental impacts of runoff and erosion are usually stressed in order to bring to the public's attention the importance and implications of soil erosion. However, few studies are aimed at calculating the economic implications of erosion, this being the message that farmers and/or policy makers understand best. In this current work we estimated the cost of erosion in vineyards in the Penedès–Anoia region (NE Spain), in which high intensity rain storms (>80–100 mm h^{-1}) are frequent. Modern plantations in the region consist of trained vines, usually planted perpendicular to the maximum slope direction. Broadbase terraces are interspersed between vine rows to intercept surface runoff and convey it out of the field. Part of the sediment generated above these terraces is deposited in them and other parts are either deposited beyond the boundaries of the fields or are exported to the main drainage network. High intensity rainfall produces heavy soil losses (up to 207 Mg ha^{-1} computed in an extreme event in June 2000, which had a maximum intensity in 30-min periods of up to 170 mm h^{-1}). To estimate the cost of erosion in vineyard fields of this region, two important aspects were considered. These were a) the cost incurred by the maintenance of the broadbase terraces, drainage channels and filling of ephemeral gullies and b) the cost incurred by the loss of fertilisers (mainly N and P) caused by erosion. According to farmers' records, the former was estimated at 7.5 tractor-hour ha^{-1} $year^{-1}$ (as average), which comprises 5.4% of the income from grape sales. Regarding N and P losses, nutrients exported by runoff were 14.9 kg ha^{-1} N and 11.5 kg ha^{-1} of P, which, if compared to the annual intakes, represent 6% and 26.1% of the N and P respectively. In economic terms, the replacement value of the N and P lost represents 2.4% for N or 1.2% for P of the annual income from the sale of the grapes.

Keywords: Soil erosion; Impacts of erosion; Nutrient loss; Cost of erosion; Vineyards

1. Introduction

Soil erosion by water on cultivated land causes a series of on-site as well as off-site damage and problems throughout the world. These include soil and nutrient loss (Poesen and Hooke, 1997; Douglas et al., 1998; Corell et al., 1999; Woodward, 1999; Gunatilake and Vieth, 2000; Steegen et al., 2001; Verstraten and Poesen, 2002; Ng Kee Kwong et al., 2002; Ramos and Martínez-Casasnovas, 2004), long-term productivity loss of degraded soils (Lal, 1995; Roose, 1996; Alfsen et al., 1996; Gunatilake and Vieth, 2000) and a wide range of environmental problems derived from sediment delivery to the drainage network and reservoirs (Hansen et al., 2002; Verstraeten et al., 2003). In this respect, and in order to assess and implement conservation measures and policies, research has being historically focused on the different erosion processes, the factors related to the development of different forms of erosion, the quantification of erosion rates and the development of soil loss prediction models and/or sediment and sediment-associated nutrient transport models (Merritt et al., 2003).

Few studies, however, have been aimed at knowing the economic implications of erosion, this being the message that farmers and/or policy makers would understand better in order to perceive and recognise the problem and to implement conservation measures, both at the field level and the catchment level. One example of these studies is the

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doi:10.1016/j.catena.2006.04.007

work by Clark (1985), which provided a national assessment of the adverse off-site effects of soil erosion on river navigation in the USA: cropland erosion contributed \$390 million to navigation costs. In the same line, Ribaudo (1986) and Hansen et al. (2002) estimated the benefits to navigation of reductions in erosion. These were quantified for different watersheds, most impacts ranging between \$0.005 and \$0.10 per ton, with maximum costs of \$5 per ton. Other studies have tackled the quantification of on-site effects more specifically. One example is the work by Walker (1982), who developed and applied an on-site damage function which incorporates a non-linear relation between crop yield (wheat) and topsoil depth in a dynamic setting, to compare conventional farming and conservation tillage and to understand the economics of the soil conservation decision. Later, Walter and Young (1986) improved the damage function by incorporating the relationship between the multiplicative technical progress and topsoil-yield, determining whether farmers with specified time horizons and discount rates should or should not adopt a conservation practice in a particular year. Since this type of productivity modelling could require numerous assumptions and field experiments, other researchers have proposed alternative methods to estimate the on-site cost of soil erosion, such as the replacement cost method (Dixon et al., 1994). It assumes that the cost incurred in replacing productive assets damaged by an economic activity can be measured and interpreted as benefits when the damage is prevented. An example of the comparison between the replacement cost method (nutrient loss) and a productivity change method (crop yield reduction in relation to topsoil depth) for estimating the on-site cost of soil erosion is provided by Gunatilake and Vieth (2000). This study reveals that, although the replacement cost estimates are 29% higher, the financial viability of soil conservation measures was consistent with the two on-site estimates.

Several reasons for the usual omission of the economic implications of erosion in soil erosion research, as stated above, can be pointed out. First, there has been little concern about soil erosion among farmers, who have not perceived it as an important problem (Verstraeten et al., 2003). On the other hand, from the field or farm point of view, it is difficult to carry out an accurate cost–benefit analysis that takes all the factors involved in final crop yield into account. For example, the value of the sediment lost due to erosion is not known. In this respect, in some studies, only the medium-term (50 years) loss in productivity through soil degradation is considered (Pimentel et al., 1995). This is based on the fact that erosion changes soil properties, removes nutrients and alters crop yields (Tengberg et al., 1998). This approach agrees with that in Alfsen et al. (1996), which stated that the cost of soil erosion is not so dependent on the physical amount of soil lost as the economic effects of these losses, and considered the loss of soil productivity as the main onsite effect. However, this concept is difficult to apply since several factors can cause a decline in soil productivity (Lal, 1987; Gunatilake and Vieth, 2000) and assigning an amount or percentage of the reduction in soil productivity to soil erosion may be complicated (Gunatilake and Vieth, 2000). On the other hand, technological improvements (e.g. fertilisers or irrigation) over time may hide the impact of soil erosion on yield reduction, making the on-site soil erosion cost analysis more difficult (Walter and Young, 1986). In other cases, the soil is considered as a non-renewable resource and maximum tolerable soil loss thresholds have been established. However, those thresholds have shown not to be universally applicable (Verstraeten et al., 2003).

Thus, although some authors consider that estimates of the specific on-site effects of soil erosion, such as the replacement cost of lost nutrients or damaged infrastructures, give only a very partial vision of the cost of erosion in agricultural fields (Alfsen et al., 1996), they can be useful to show the dimension of specific problems at the field scale in the short-term, without the need for long yield data sets, (Gunatilake and Vieth, 2000).

In the present work, the cost of erosion was estimated in vineyard fields in the Penedès–Anoia region (NE Spain). Specific on-site effects, such as the replacement cost of nutrients lost over the year and the cost incurred in the maintenance of drainage channels and filling of ephemeral gullies that appear in the vineyards as a result of high intensity rainfalls, have been assessed. In this respect, some evaluations carried out in the Mediterranean region of Europe, representing different landscapes and land uses, conclude that vineyards are the lands that incur the highest runoff and soil losses. Examples include 47–70 Mg ha^{-1} yr^{-1} in NW Italy (Tropeano, 1983), 35 Mg ha^{-1} yr^{-1} in the Mid Aisne region (France) (Wicherek, 1991), 22 Mg ha^{-1} yr^{-1} in the Penedès region (NE Spain) (Usón, 1998), 18–22 Mg ha^{-1} due to rill erosion measured between September and November (Ramos and Porta, 1997), 34 Mg ha^{-1} in extreme rainfall in SE France (Wainwright, 1996), or 207 Mg ha^{-1} in extreme rainfall in the Penedès region (NE Spain) that had an erosivity index R of 11,756 MJ ha^{-2} mm h^{-1} (Martínez-Casasnovas et al., 2002). However, most of the soil erosion research carried out in vineyards only focuses on soil loss; less work has been done to investigate nutrient losses associated with soil erosion during the storms (Ramos and Martínez-Casasnovas, 2004). On the other hand, in the case of areas where high intensity rainfalls are frequent, as in the Mediterranean region, another important effect on agricultural fields is the incision of ephemeral gullies caused by concentrated overland flow. This is of particular relevance in vineyards with partial soil cover (Meyer and Martínez-Casasnovas, 1999). In such cases, ephemeral gullies constitute the main drainage systems for a field, through most water and sediment are delivered off-site (Zheng and Huang, 2002), accounting for between 44% and 83% of total sediment production (Poesen et al., 1998; Martínez-Casasnovas et al., 2002). As is known, ephemeral gullies can easily be obliterated by normal tillage or filled by farmers because the scoured soil volume is not usually very large (Woodward, 1999; Bennet et al., 2000). Those recurrent filling operations, together with the maintenance conservation measures (e.g. the emptying of broadbase terraces that are interspersed between vine rows), to avoid the development of a permanent and deep gully network, suppose a additional annual cost for the exploitation that is not usually computed and registered as a cost due to erosion.

With this research work, we hope to contribute to making farmers aware of the consequences of some important economic implications of soil erosion, in order to point out to them the necessity of implementing conservation measures. Moreover, we aim to show them that although the costs of implementing soil conservation measures are immediate, the benefits will appear in the short term.

2. Material and methods

2.1. Study area

The Penedès–Anoia region is located in Catalonia (Spain) (41° 28′N, 1° 48′E) (Fig. 1). Vineyards are the main land use, representing 80% of the cultivated area. This area is part of the Penedès Tertiary Depression, with calcilutites (marls) as the main lithological material and occasional sandstones and conglomerates. According to Soil Taxonomy (Soil Survey Staff, 1998), the most frequent soils are classified as *Typic Xerorthents* and *Typic Calcixerepts* (Martínez-Casasnovas, 1998). In recent decades, land levelling has been a frequent practice in the study area with the aim of making larger and more-easily mechanised fields, which has involved the elimination of numerous soil conservation measures. Most soil profiles have been truncated either by erosion or by land levelling.

The climate is Mediterranean, with a mean annual temperature of 15 °C and a mean annual rainfall of 550 mm (Ramos and Porta, 1994). Rainfall mainly occurs in two periods: September to November and April to June. High-intensity rainstorms are frequent during the first period (e.g.> 100 mm h^{-1} in 5-min periods). The rainfall erosivity factor (R) ranges between 1049 and 1200 MJ mm ha^{-1} h^{-1} yr^{-1} (Ramos, 2002).

2.2. Vineyard characteristics and management practices

The case study vineyard has an area of approximately 2.12 ha (Fig. 1). The average slope of the plot is 8.9%. The plantation consists of trained vines, in a 1.3 × 3.1 m pattern, which run along the contour (perpendicular to the maximum slope direction). Three grape varieties are planted in the field: Macabeo, Chardonay and Parellada. The summary of the area planted, the yield of the year 2003 and the price obtained are presented in Table 1.

Every eight rows, there is a hillside ditch or broadbase terrace (locally named “rasa”). Their function is to intercept surface runoff and convey it out of the field. Part of the sediment generated above these ditches is deposited in them and is later used and redistributed by farm machinery to fill ephemeral gullies caused by erosive rainfalls.

The usual fertilisation practice consists of one yearly application (in January) of a blending fertiliser at a rate of 500 kg ha^{-1}. The fertiliser units of this blend are: 4 N–6 P–

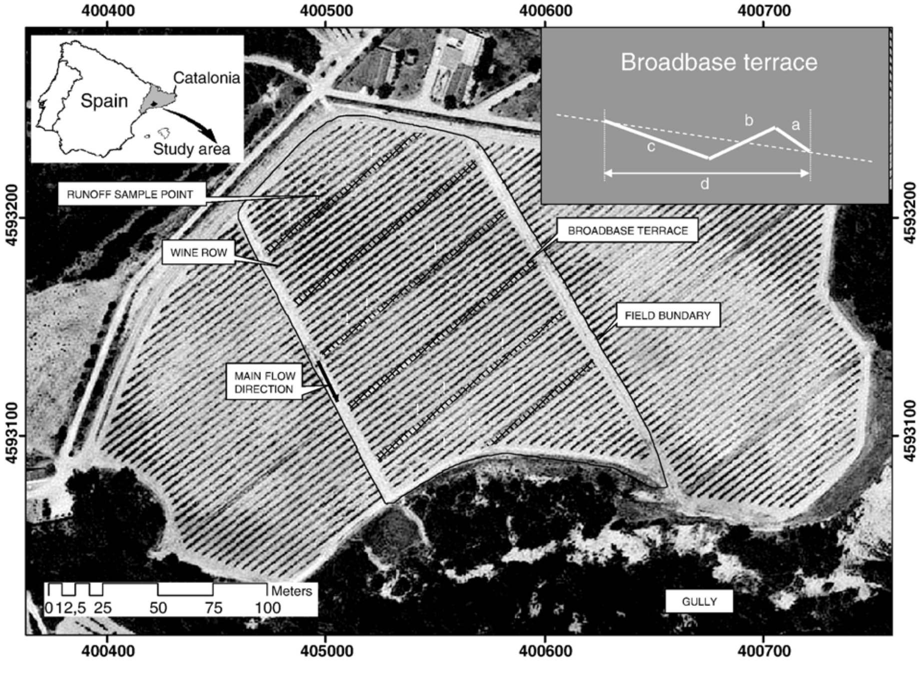

Fig. 1. Location of the study area, characteristics of the vineyard field and location of runoff sample points.

Table 1
Grape varieties and yield (year 2003) in the case study vineyard field

Variety	Area planted (ha)	Yield 2003 (kg)	Price (€ kg^{-1})
Macabeo	0.58	2950	0.32
Chardonay	0.48	1530	0.81
Parellada	1.06	20,540	0.27

2 MgO–1 Fe–40 S+15% of organic matter. The cost of this product for the year 2003 was 0.21 € kg^{-1}. In addition to this application, 40 Mg ha^{-1} of composted cattle manure is added every four years. This has become a common practice in the Penedès–Anoia area to improve soil properties. The application is usually made in alternate vine rows and it is incorporated in the upper 25 cm. The organic matter content of the compost is 82.7%, with a total concentration of N of 22.6 mg g^{-1} (of which 17.6 mg g^{-1} is organic N) and 1411 mg kg^{-1} of P, among other components. The price paid by the farmer for this manure in 2003 was 0.02 € kg^{-1}.

2.3. Assessment of nutrient losses

The assessment of nutrient losses due to erosive rainfall was based on field measurements of runoff collected at 12 sample points along and across the field (Fig. 1), in which Gerlach type collectors (50-cm width) were installed. Total runoffs were modelled using a soil–vegetation–atmosphere–transfer model (SVAT), which includes physically based representations of interception, infiltration, drainage, transpiration, soil evaporation, canopy evaporation and runoff. Total runoff generated in each erosive event was related to the volumes recorded in the collectors. Those runoff samples were collected after the main rainfall events occurred during 2003, and for the same periods the accumulated runoff was also modelled. A good fit between recorded and modelled runoff was observed. From this information, total soil and nutrient loss for the whole field were computed.

The meteorological inputs required for modelling the water balance were hourly rainfall and daily temperature. Rainfall was recorded at 1-min intervals in the same field using a tipping-bucket rain gauge connected to a data-logger. The hourly information was calculated from that data. Daily temperature was obtained from the meteorological station located in Els Hostalets de Pierola (Institut Meteorològic de Catalunya), sited 10 km from the farm. Other inputs required by the model were a digital elevation model (Martínez-Casasnovas et al., 2002) (used for modelling overland flow paths and solar radiation received), land cover (as an input to the vegetation module), soil characteristics such as hydraulic conductivity, bulk density, erosionability and sealing, which were obtained from field measurements.

The nutrient concentration in the sediments trapped in the Gerlach collectors (total N and total P) was analysed according to the methods developed by Bremner and Mulvaney (1982) and Olsen and Sommers (1982).

2.4. Assessment of maintenance of drainage channels and filling of ephemeral gullies

As stated above, the farmers redistribute part of the sediment displaced by erosive rainfalls. This sediment usually comes from areas adjacent to the ephemeral gullies, thus reducing top soil depth, and also from the hillside ditches and/or from low parts of the field that surround the field, which act as sediment traps before the sediment reaches the permanent drainage system. The sediment redistribution operations involve some costs in terms of labour and machinery that, for this study, were evaluated from a direct inquiry to the farmer. These specific maintenance operations suppose an average of 7.5 h ha^{-1} $year^{-1}$, which represents 180 € ha^{-1} $year^{-1}$ (€=Euro) (according to the price of labour and cost of machinery for the year 2002/03 paid in the case study farm, 24 € h^{-1}, this being representative of the area).

3. Results and discussion

3.1. Nutrient losses

In terms of total rainfall (about 640 mm), 2003 can be considered an average year, although the rainfall distribution did not fit the typical Mediterranean pattern. Heavy rainfall was recorded in autumn and at the end of winter. The main differences with respect to the typical average year occurred in spring, which was drier than usual. Table 2 summarises rainfall, runoff and the sediment and nutrients mobilised by runoff in the different rainfall periods recorded during the year. The sediment and nutrient mobilised was computed from the average of the 12 sample points located in the field and from the runoff data generated by the SVAT model, taking into account the sediment/runoff ratio registered in the Gerlach collectors.

Most rainfall in winter and spring was of low intensity and runoff during that season was scarce. However, in autumn, the runoff rates were relatively high. Total soil lost by runoff was estimated in 19.5 Mg ha^{-1}. Total N losses were 14.9 kg ha^{-1} and total P losses were 11.5 kg ha^{-1}. If compared to the annual intakes, 246 kg ha^{-1} of N, and 44.1

Table 2
Rainfall, runoff, soil and nutrients mobilised by runoff (N and P) for different periods during 2003

Period	Rainfall mm	Runoff L m^{-2}	Sediment Mg ha^{-1}	N kg ha^{-1}	P kg ha^{-1}
1/1–20/1	11.2	1	0.06	0.04	0.05
20/1–5/3	124.6	13	0.39	0.28	0.17
5/3–4/3	10.2	0.5	0.64	0.06	0.04
3/4 – 26/5	126	21	3.46	4.84	2.92
26/5–16/9	24.8	9.4	7.77	3.89	4.93
16/9–3/11	222	34.6	5.42	4.87	2.59
3/11–10/12	129.4	22	1.43	1.00	0.86
Total	647.4	98.5	19.98	14.9	11.5

ha^{-1} of P (computed from the blending fertiliser and organic compost composition), these losses represent 6% and 26.1% of the annual N and P intakes respectively. The percentage of P that was lost could seem to be too high although, as is known, P is mainly absorbed in the upper soil horizon, which is directly affected by runoff. In economic terms, and in relation to the annual income from the sale of the grapes (which was 3312 € ha^{-1} in the case study vineyard for year 2003), the replacement value of the amount of N and P lost represents 2.4 % for N or 1.2% for P.

In comparison with the nutrient losses measured in the field itself due to the extreme rainfall event recorded on 10th June, 2000, (total rainfall of 215 mm, 205 mm of which fell in 2 h 15 min and with a maximum intensity in 30-min periods of 170 mm h^{-1}) (Ramos and Martínez-Casasnovas, 2004), the amount of N lost in the whole of 2003 was much lower (14.9 kg ha^{-1} in 2003, versus 108.5 kg ha^{-1} in the extreme event of 2000), as well as the amount of P lost in 2003 (11.5 kg ha^{-1} of P in 2003 versus 108.6 kg ha^{-1} of P in the extreme event of 2000). However, the proportion of those nutrients with respect to the net soil loss was higher in 2003 than in the extreme event of 2000. These differences are due to the characteristics of the extreme rainfall and the relative importance of the different erosion processes that occurred in the field. The dominant process in the extreme event of 2000 was concentrated runoff, which accounted for 58% of total soil detached (Martínez-Casasnovas et al., 2002). In this case, most of the sediment mobilised occurred in ephemeral gullies (up to 0.4–0.5 m deep), where the N and P concentration is much lower than in the soil surface, which in contrast, is most heavily affected by the usual rainfall.

3.2. Maintenance of drainage channels and filling of ephemeral gullies

According to the information provided by the farmer, the cost of maintenance of drainage channels and filling ephemeral gullies, including the redistribution of the sediment over the field and repairing the hillside ditches, represented a cost of 381.9 € for the whole field. This represents an average cost of 180 € ha^{-1} $year^{-1}$. That represents 5.4% of the income from the sale of the grapes (3312 € ha^{-1}). This figure cannot be compared with the results from other soil erosion study areas owing to the lack of this type of information in these.

This cost should not be avoided by the farmer by not maintaining or removing the broadbase terraces and not filling the ephemeral gullies. In the case of the broadbase terraces, Martínez-Casasnovas et al. (2002) showed that although their main function is to intercept surface runoff and convey it out of the field, they also act as sediment traps. Then, if those terraces did not exist (“without” case), the sediment trapped in them would have been transported out of the field via the ephemeral gullies, and the soil loss would have increased by 31.5% over that actually observed. This would have avoided the cost of terrace maintenance and gully filling (180 € ha^{-1} $year^{-1}$), which supposes the main replacement cost of the two evaluated. However, it would have increased the cost of nutrient replacement by 3.1% of the total cost for N or up to 1.6% for P. The difference with respect to the “with” case (existence and maintenance of the broadbase terraces and gully filling): 2.4 % versus 3.1% for N or 1.2% versus 1.6% for P; could be seen as little important and thus the necessity of maintaining the conservation practices. However, in the case of non-maintenance, ephemeral gullies reform in the same locations with additional runoff events and can grow into large gullies (Woodward, 1999; Bennet et al., 2000), producing significant local topographic changes in the medium-long run and much more soil loss.

4. Conclusions

The present work reveals the importance of on-site erosion effects on the final budget of vineyards in the Penedès–Anoia region, examined through the quantification of the replacement cost of the nutrient lost or infrastructures damaged. In this case study, these costs supposed respectively 6.6% and 7.8% of the income from the sale of the grape production, the last in the most unfavourable situation due to the replacement of N. This, however, is a default figure, since it does not take into account other possible on-site effects, such as damage to other field infrastructures and the long-term loss of soil productivity. In addition, and in order to obtain a global view of the erosion problem in the region, off-site problems, such as non-point source pollution would have to be considered.

The consideration of the “without” case conservation practices (non-existence of broadbase terraces and no filling of ephemeral gullies) has shown to be economically more favourable for the farmer in the short term than the “with” case. However, in the long run, damage could dissect the field by the incision of gullies and the destruction of vineyard training infrastructures, making farming less and less profitable.

Also we know that while the results of the research only give a partial vision of the cost of erosion in the vineyards in this region, they can be useful to show the dimension of the problem at field scale in the short-term without the need for long yield data sets. In addition, the translation of the on-site erosion effects into economic terms will benefit the understanding of the problem by farmers and/or policy makers, letting them see the need to promote and/or implement soil conservation measures, as that is the language that they usually understand best.

Acknowledgements

As part of the REN2002-00432 Project “Soil and water degradation derived from land transformation, land use and management practices changes and climatic variability in vineyards of the Mediterranean area", 2002/04, this study was undertaken with funding from the *Comision Interministerial de Ciencia y Tecnologia* (Inter-ministerial Commission for Science and Technology) (CICYT).

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