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Runoff, sediment and nutrient exports from a Mediterranean vineyard under integrated production: An experiment at plot scale

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ABSTRACT

Conventional management of Mediterranean vineyards strongly contributes to land degradation. In Portugal, the use of integrated production has been encouraged by governmental subsidies because it is assumed to be a farm management system that protects the environment and favours agriculture sustainability. The purpose of this study is to assess the impact of minimum tillage and regulated fertilization practices, driven by integrated production, on runoff and associated sediment and nutrient exports (total phosphorous – TP, total nitrogen – TN and nitrates – NO_3). A vineyard in the Bairrada wine region was instrumented with six runoff plots (80–122 m^2). Plots were monitored on a weekly to bi-weekly basis (depending on the rainfall pattern), over two hydrological years (from October 2012 to September 2014). Results indicated that annual runoff coefficients ranged from 10% to 20%, sediment losses from 1.1 to 29.0 Mg ha^{-1} yr^{-1}, TP exports from 0.4 to 6.5 kg ha^{-1} yr^{-1}, TN exports from 0.2 to 20.0 kg ha^{-1} yr^{-1} and NO_3 exports from 0.1 to 0.8 kg ha^{-1} yr^{-1}. These results highlight the susceptibility of vineyards to land degradation and their role as a diffuse source of pollution. Rainfall strongly influenced runoff as well as sediment and nutrient concentrations, leading to relevant inter-annual and seasonal differences. Over the study period, about 60% of runoff and > 85% of sediments and nutrients exported by runoff were recorded during winter. Management practices, namely inter-row tillage deeply influenced sediment exports, whereas fertilization, had a strong effect on nitrate exports. Although integrated production lead to lower runoff and nutrient exports than conventional viticulture, additional measures are needed to effectively prevent soil erosion and nutrient losses in Mediterranean vineyards.

1. Introduction

Vineyards are one of the most important fruit crops in the world, covering 7.5 million ha and producing 267 million hl of wine (OIV, 2017). The European Union embraces 39% of the world grape production, with Portugal being its fourth largest wine producer, comprising 190 000 ha of vineyards (OIV, 2017), which represents 27% of the area occupied by permanent crops (INE, 2017). Wine production is one of the most important economic sectors in Portugal, assuring 52% of drinking industry sales (INE, 2017). Besides the unquestionable relevance for the Portuguese economy, some wine regions are also cultural landscapes and were recognized by UNESCO as World Heritage (e.g. the Douro region), thereby having great impact on tourism.

Despite its economical relevance, vineyard sustainability may be endangered due to land degradation, linked with soil erosion and nutrient losses, which hinders the growth of plants and agricultural yield potential (Issaka and Ashraf, 2017; Novara et al., 2017). In the Mediterranean region, vineyards are reported as one of the land uses with highest erosion rates (Prosdocimi et al., 2016; García-Ruiz et al., 2017; Rodrigo-Comino et al., 2018) and identified as one of the major threats to long-term agricultural sustainability (Casalí et al., 2009; Biddoccu et al., 2016). Reports of erosion rates in Mediterranean vineyards are widely variable but attain 2.7–4.7 Mg ha^{-1} yr^{-1} in NW Italy (Biddoccu et al., 2017), 11.51 Mg ha^{-1} yr^{-1} in Anoia–Alt Penedès region, NE Spain (Ramos and Martínez-Casasnovas, 2006) and 16 Mg ha^{-1} y^{-1} in Sicily (Novara et al., 2017). These rates are higher than soil erosion under natural, non-cropped conditions, even for steep slopes (1.6 Mg ha^{-1} yr^{-1} in 63% slopes; Nearing et al., 2017), and above the tolerable/acceptable soil losses that assure land sustainability (1 Mg ha^{-1} yr^{-1}; Verheijen et al., 2009).

The main reasons for the high erosion rates in Mediterranean vineyards include: (i) a reduced soil cover over the year (particularly

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during the rainy season), which leaves the soil surface exposed to rainfall, thereby favouring water and sediment losses (e.g. Casalí et al., 2009); (ii) climate conditions, namely the occurrence of high intensity rainfall events in spring and autumn (e.g. Martínez-Casasnovas et al., 2005); and (iii) high soil erodibility, since vineyards are usually planted on steep-slopes (García-Ruiz, 2010), so the soils have low nutrient and organic matter contents (Novara et al., 2011; García-Díaz et al., 2017b), and therefore low structural stability and aggregation (Ruiz-Colmenero et al., 2013).

Land management practices are also an important driver of land degradation. Conventional vineyards, focused on maximizing commercial production, use high inputs of fertilizers and several phytopharmaceutical products, such as herbicides, and use intensive tillage for soil decompaction and weed control (mechanical weeding) (Novara et al., 2011; Chevigny et al., 2014; Prosdocimi et al., 2016). The use of mechanisation may locally influence soil compaction and decrease infiltration, favouring runoff and soil erosion (Chevigny et al., 2014), which trigger problems to the drainage network and reservoirs siltation (e.g. Martínez-Casasnovas and Ramos, 2006). Diffuse contamination from agriculture has been considered one of the major threats to water resources, namely due to nutrient and pesticide losses from vineyards (e.g. Cerqueira et al., 2005; Ferreira et al., 2010).

Water and soil protection are mandatory for European countries, through the Water Framework Directive (EC, 2006) and the Soil Thematic Strategy (CEC, 2006). To achieve these goals, the governments provide economic incentives to farmers, in order to adopt sustainable management practices. In Portugal, for example, 75% of financial support to implement Agro-Environmental Measures for integrated protection was assigned to vineyards (Amaro, 2003). Integrated production is regulated by the principles of soil preservation and fertility improvement, which imposes the existence of a soil protection cover during the wet season and maximum allowable fertilization rates (Mailly et al., 2017).

Although some researchers have investigated the impact of sustainable viticulture practices, such as minimum tillage (e.g. Ramos and Martínez-Casasnovas, 2006), the use of catch crops (Bonfante et al., 2015) or the application of straw mulches (e.g. Prosdocimi et al., 2016), the contribution of integrated production to minimize land degradation have been overlooked. Furthermore, most of these studies focus on runoff and erosion, without considering the associated nutrient losses. Hence, the main objectives of this study were to: (i) quantify surface runoff, sediment and nutrient (total P, N and NO_3) losses in a Portuguese vineyard under integrated production; and (ii) relate these losses with environmental variables and management practices (tillage and fertilization practices used in integrated production). Assessing the sustainability of vineyards under integrated production is important not only to guaranty crop productivity but also to evaluate the effectiveness of management practices receiving financial support from governmental agencies.

2. Methodology

2.1. Study site

This research was carried out in a commercial vineyard in São Lourenço (40° 25′ 58″N; 8° 30′ 6″W), a small catchment (6.2 km^2) in North-Central Portugal (Fig. 1). This vineyard is included in the specialized wine region of Bairrada, which accounts for 3.6% of the Portuguese wine production (INE, 2017) and includes some top-quality wines that have been distinguished in national and international contests. The São Lourenço stream transports a considerable load of sediments (attaining occasionally 60 t day^{-1}; Serpa et al., 2015). It is a tributary of Cértima River, where pollution problems have been documented in a few sections of ifs main course, mostly regarding biochemical oxygen demand, Kjeldahl nitrogen and total phosphorus (Cerqueira et al., 2005; Ferreira et al., 2010). Eutrophication is visible in some of the river stretches, with large amounts of vegetation developing periodically. The Cértima River is the principal source of water flowing into the Pateira de Fermentelos, the largest natural lake of the Iberian Peninsula.

The studied vineyard was planted in 2012, according to slope orientation. It has a plant density of 3460 vines ha^{-1}, with plants 1.3 m apart in straight rows and inter-rows distance of 2 m. This vineyard has been following integrated production since 2007, with minimum tillage and regulated application of fertilizers and phytosanitary treatments (in terms of products and maximum application rates). Tillage is performed twice a year (usually in spring and autumn), using a chisel with 5–7 nozzles, which rips the soil at 10 cm depth (non-inversion of soil layers). Tillage is performed only between some inter-rows, to maintain partial vegetation cover. Tilled inter-rows change every time, so that soil is not mobilized more than once per year. Weeds in the vine rows are controlled chemically once or twice per year, through herbicide (glyphosate) application, between March and July. Pre-emergent fungicides are applied about eight times per year, between March and August. Foliar fertilizers are applied twice per year, between May and July. Tractors with dispersers are used in pesticide and foliar fertilizer application. Fertilization may be complemented with manure application during tillage. Pruning and harvesting are performed manually in January and October, respectively. The vineyard is exclusively rain fed, so there is no irrigation even during the dry season.

The climate in the region is Mediterranean but there is a strong influence of the Atlantic Ocean. Between 1971 and 2000, the average annual rainfall was 1077 mm in Oliveira do Bairro, ~8 km from São Lourenço, with the following seasonal distribution: 7.5%, 29.7%, 38.0% and 24.7% respectively in summer (June–August), spring (March–May), autumn (September–November) and winter (December–February) (SNIRH, 2014). During the same period, the average annual temperature was 15.7 °C (SNIRH, 2014). The slopes in the catchment are gentle (< 10%) and the soils are typically Calcaric Cambisols with a clay texture (Serpa et al., 2015).

2.2. Experimental design and sampling

Six plots (P1–P6) were established in a commercial vineyard under integrated production to monitor runoff, total suspended solids (TSS) as well as nutrients concentrations and exports (total phosphorus: TP, total nitrogen: TN and nitrates: NO_3). The plots were installed in the inter-row zone and were naturally bounded by a path on the top and by vine strips on the sides (elevated soil surface). At the outlet of each plot, a collector grid was buried beneath the soil surface. The collector grid was connected to a tipping-bucket device, which in turn was connected by a garden hose to an 80-L tank that collected runoff (Fig. 2). Plot design had to be simple to avoid disturbance of vineyard management practices, particularly tractor traffic. Plot installation was completed on mid-September 2012. Frequent runoff leakages, derived from construction problems, were observed in plots P3 and P6 over the study period. Since data quality was not assured, both plots were excluded from the study. The drainage area of the four plots included in the study ranged from 79.9 m^2 to 122.0 m^2 (Table 1).

Data collection started in October, about two weeks after the installation in order to mitigate soil disturbance with plot outlet installation. Plots monitoring was performed over two hydrological years (until September 2014). Runoff accumulated in the tanks was measured and collected on a weekly or by-weekly basis, depending on rainfall occurrence. Under warm settings runoff samples were collected immediately after the storm, in order to avoid water quality changes. Homogeneous samples (after stirring) for TSS analyses were collected in 1500-mL plastic bottles, whereas those for nutrient analyses were stored in acid-washed 250-mL polyethylene bottles. Samples were taken to the laboratory in a cooler (~4 °C).

Due to tipping-bucket's malfunction only cumulative runoff data was recorded. An automatic rainfall gauge was installed a few meters

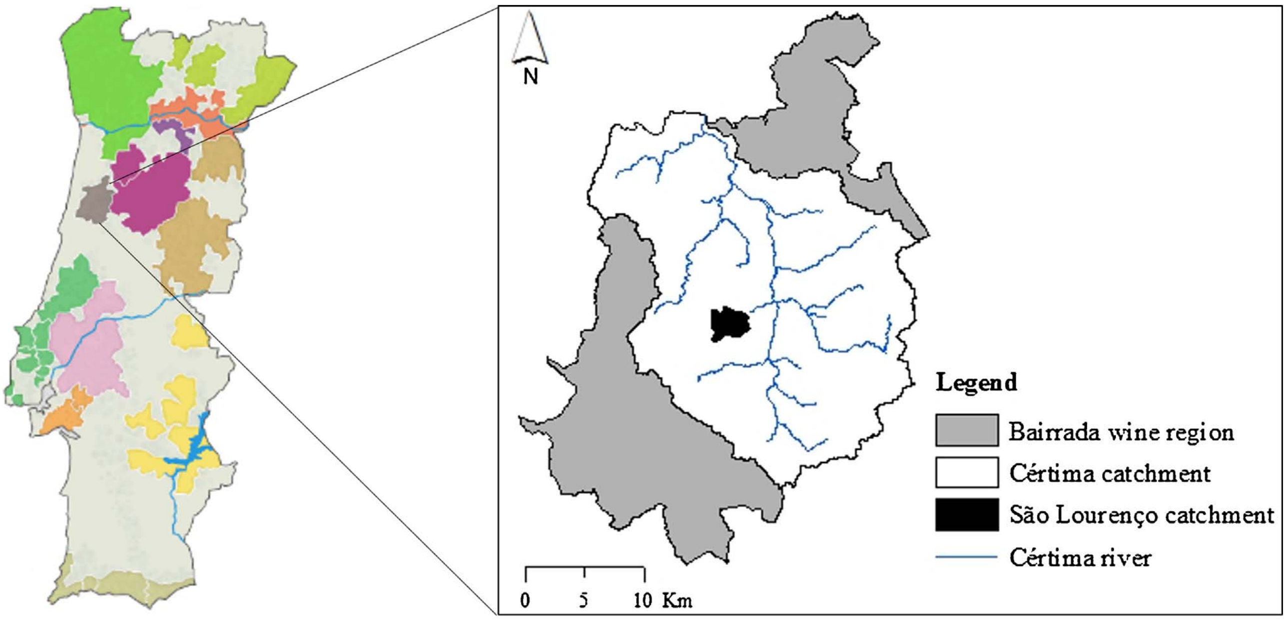

Fig. 1. Wine regions in Portugal mainland (left) including the Bairrada region, Cértima River and São Lourenço catchment (right).

from the plots to measure rainfall over the study period.

The management practices performed over the study period, namely tillage and fertilization operations are summarized in Table 1. The operations implemented in the vineyard were decided by the farmer according with the integrated production guidelines, and affected the plots without any interference from the researchers. Thus, tillage was performed in P1 at the same time as P5, whereas P2 and P4 were tilled in distinct periods.

2.3. Laboratory analysis

Samples for TSS analyses were stored at room temperature (± 20 °C). Samples for nutrient analyses were filtered through 0.45-μm membranes (Millipore MF) and stored at −20 °C. Before chemical analyses, these samples were defrosted at room temperature.

Total suspended solids were analysed gravimetrically by filtration of runoff samples through 0.45-μm membranes (Millipore MF) following by drying at 105 °C, as defined by the 2540 D method from APHA

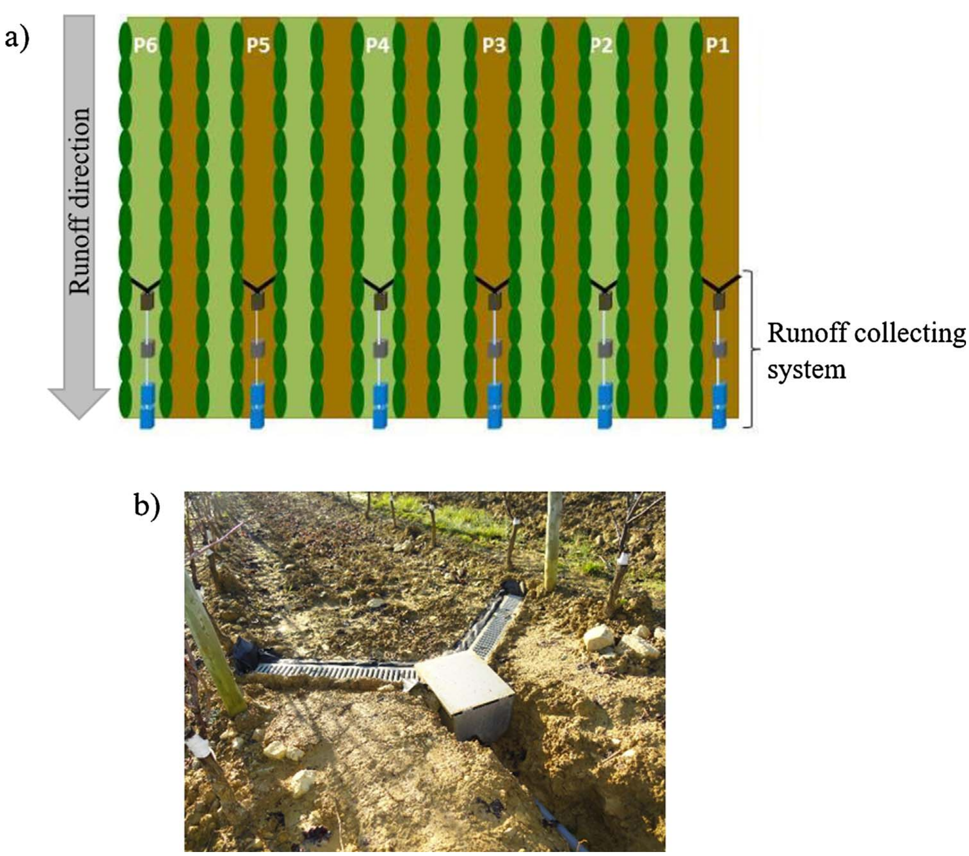

Fig. 2. Runoff plots: a) experimental design (green dark: vine; green light and brown represent untilled and recently tilled inter-row when plots were installed), and b) runoff collecting system, consisting of a tipping bucket connected to a tank (not visible) by a garden hose. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Plot characteristics and description of management (tillage and fertilization) practices. The timing of fertilization, type and amount of fertilizers applied were based on technical recommendations provided by APIBAIRRADA to local farmers.

Plots	P1	P2	P4	P5
Length (m)	50.9	48.4	61.0	40.0
Area (m^2)	101.7	96.8	122.0	79.9
Slope (%)	5.0	6.0	7.0	6.0
Tillage (10 cm depth)	24/09/2013	27/09/2012 04/06/2014	27/09/2012 04/06/2014	24/09/2013
Fertilization	24/05/2013: Manure application (300 kg ha^{-1}) 15–25/06/2013: Foliar fertilizer, including: AMINOBORO (1 L ha^{-1}) ALGABIOL (1.5 L ha^{-1}) FOLUR (2 L ha^{-1}) 19–25/07/2013: Foliar fertilizer, including: AMINOVIT (2 L ha^{-1}) FERTAFOL 12-5-35 (2.5 L ha^{-1}) FERTILEADER (3 L ha^{-1}) 21–24/05/2014: Foliar fertilizer, including: AMINOBORO (1 L ha^{-1}) ALGABIOL (1.5 L ha^{-1}) FOLUR (2 L ha^{-1}) 19–26/06/2014: Foliar fertilizer, including: FERTILEADER 9-5-4 (2.5 L ha^{-1}) FERTILEADER 4-6-9 (3 L ha^{-1})			

(1998). TP, TN and NO_3 were measured with an automated flow injection analyser (FOSS FIAstar 5000) using the colorimetric method, according to the ISOs 15681-1, 11905 and 13395, respectively. The detection limits for nutrient analyses were 0.01 mg L^{-1}, 0.1 mg L^{-1} and 0.005 mg L^{-1} respectively for, TP, TN and NO_3.

2.4. Data analysis

In view of the non-normal distribution of runoff, sediment and nutrients (TP, TN and NO_3) data, investigated through the Kolmogorov-Smirnov test ($p < 0.05$), a nonparametric Kruskal–Wallis H test was used to assess differences between plots over the two hydrological years. This test was also applied to investigate seasonal differences between rainfall and the above mentioned parameters. Whenever significant differences between plots were found, a Post-Hoc Least Significant Difference (LSD) test was used to identify which plots were distinctive. The significance of tillage activities on runoff, sediment and nutrient exports was examined through a Mann-Whitney *U* test, based on tillage dates and assuming a tillage stage from tillage date until subsequent tillage date of distinct plots. A Spearman's rank correlation was used to assess the relationships between rainfall, runoff, sediment and nutrient concentrations/exports. The same test was used to evaluate the link between the latter parameters and the number of days since tillage and fertilization. All tests were done at a 95% level of significance ($p < 0.05$).

3. Results

3.1. Rainfall-runoff response and sediment delivery

Annual rainfall was 1200 mm in 2012/13 and 1693 mm in 2013/14, so these are considered wet years since rainfall values were higher than the mean for the period between 1971 and 2000 (1077 mm). In 2012/13, runoff was 12%–40% lower than recorded in 2013/14 for all plots (Fig. 3a). Rainfall was significantly correlated with runoff amounts and coefficients ($r = 0.822$ and $r = 0.635$, respectively; $n = 65$; $p < 0.01$). Significant seasonal differences were recorded in rainfall and runoff coefficients ($p \leq 0.05$). The later ranged from less than 2% in summer to 16–37% in winter (Fig. 4a). During spring runoff ranged from 1.5–2.5% in 2013 to 14.4–21.2% in 2012, whereas in autumn it ranged from 2.0 to 9.4%.

Over the study period, plots P1 and P5 (tilled twice) showed slightly higher runoff (17–18%) than P2 and P4 (11–14%, tilled once) ($p > 0.05$; Fig. 4a). Runoff was influenced by management activities, with higher values recorded after tillage. For example, during the largest rainfall period (359 mm), recorded in 07/01/2014, runoff reached 126–183 mm in P1 and P5, tilled three months earlier, and only 96–99 mm in P2 and P4, tilled about one year before (Fig. 3a).

TSS concentrations were highly variable over the 2-years of study, ranging from 0.06 g L^{-1} to 13.50 g L^{-1} in the monitored vineyard (Fig. 3c). This variation is largely driven by rainfall and runoff patterns, as corroborated by the strong positive correlations between TSS concentrations and rainfall as well as runoff ($r = 0.790$ and 0.764, respectively, $p < 0.01$; Table 2). No significant differences were identified between plots ($p > 0.05$).

TSS concentrations were enhanced by tillage, as found for runoff. Over the first year, P2 and P4 (tilled in 27/09/2012) displayed higher values than P1 and P5 (1.1- to 2.1-fold) in 40% of the measurement periods, while runoff was somewhat higher only in 23% of these periods. After the second soil tillage, in late spring 2014, P2 and P4 exhibited TSS concentrations 1.5–4.6 times greater than P1 and P5, when runoff coefficient did not surpass 4% (Fig. 3b). In P1 and P5, TSS attained the highest concentrations immediately after tillage, in 04/10/2013 (13.50 g L^{-1} and 13.35 g L^{-1}, respectively; Fig. 3c), although relatively low runoff was generated (Fig. 3a). These concentrations were 2.3 and 1.8 times greater than measured in tilled P2 and P4.

Similarly to runoff, soil losses did not changed significantly between plots ($p > 0.05$). Mean annual values were 12.9 Mg ha^{-1}, 16.2 Mg ha^{-1}, 7.1 Mg ha^{-1} and 10.7 Mg ha^{-1}, respectively for P1, P5, P2 and P4 (Fig. 4b). Sediment exports varied seasonally, and were mostly provided during winter (83–91% of mean annual exports per plot; $p < 0.05$). Nevertheless, great inter-annual differences were noticed, with total sediment losses in winter 2013 being 9–15 times higher than in winter 2012. This inter-annual variability was coupled to a difference of 380 mm in winter rainfall (875 mm and 495 mm in winter 2013 and 2012, respectively), which led to runoff values of 2.0- to 2.8-fold higher (Fig. 4a). Nevertheless, week correlations between sediment exports and rainfall, as well as runoff, were recorded ($r = 0.220$ and 0.272, $p < 0.01$; Table 2).

Sediment exports seem to be influenced by tillage, albeit no significant correlation was identified (Table 2). Sediment exports were 1.3–2.4 times higher in P1 and P5 (twice tilled plots) than in P2 and P4 (once tilled plots), except in summer 2014. At this time, P2 and P4 showed mean sediment loads 6.3 times greater than recorded in P1 and P5, due to tillage in late spring 2014.

3.2. Nutrient exports through runoff

TP, TN and NO_3 concentrations in runoff are shown in Fig. 5. Similar temporal patterns were observed for TP (ranged from 0.04 to 2.99 mg L^{-1}) and TN (0.22–7.44 mg L^{-1}) in all plots, with higher values in 2013/14 than in 2012/13 and higher concentration driven by high rainfall events. The reverse was observed for NO_3 (0.01–1.69 mg L^{-1}), with higher concentrations in 2012/2013 than in 2013/2014, mostly driven by relatively small rainfall events ($\leq$37 mm). No significant differences in nutrient concentrations were identified between plots ($p > 0.05$).

Nutrient concentrations in runoff surpassed the minimum quality standards for surface waters established by the Portuguese legislation (Decree-Law 236, 1998) – TP = 1.0 mg L^{-1} and total Kjeldahl nitrogen (organic forms) of 2.0 mg L^{-1} (TN and NO_3 are not regulated). TP threshold was exceeded in 9–15% of the measurements ($n = 34$), mainly during winter rainfalls. Kjeldhal nitrogen (Nk), currently assumed as the difference between TN and NO_3 (admitting low ammonia content in the soil), was surpassed in 12–29% of the measurements ($n = 34$), mostly recorded in winter and autumn, but also in spring.

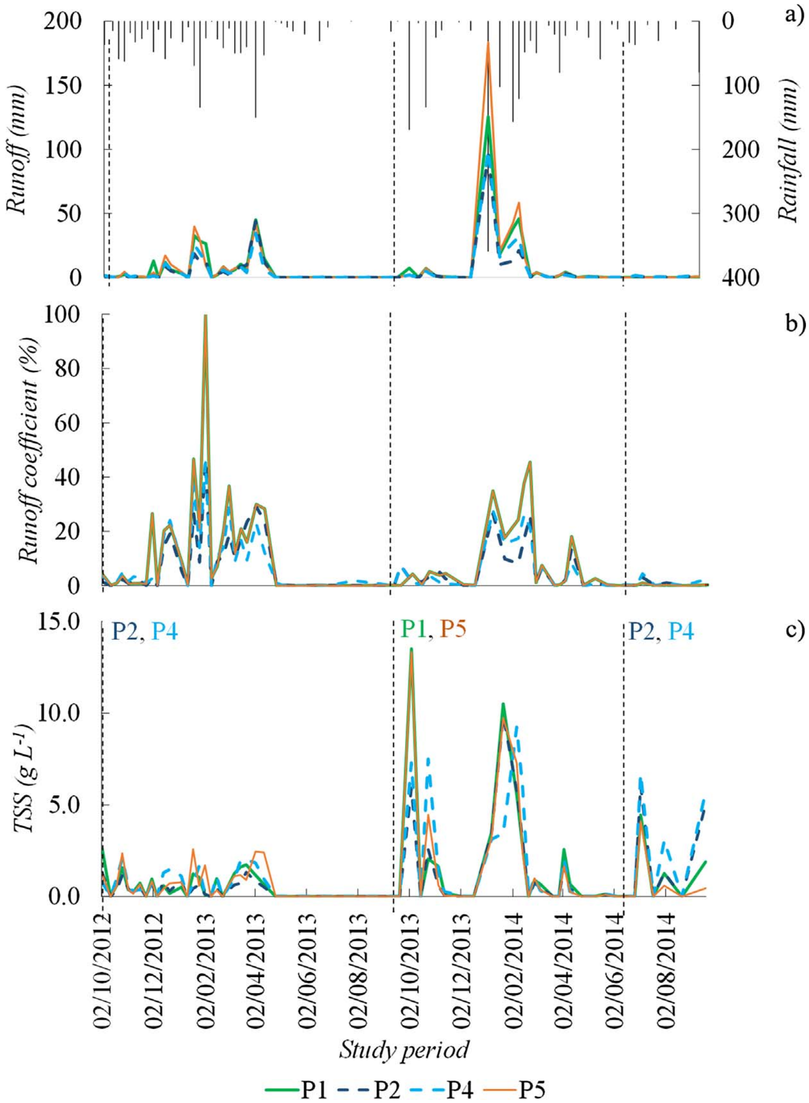

Fig. 3. Rainfall, runoff amount (a) and coefficient (b), and total suspended solid concentrations (TSS) (c) variation patterns in the four runoff plots, over the study period. Vertical dashed lines indicate dates of tillage activities.

Foliar fertilization in spring and summer 2014 (Table 1) could have contributed for the highest TP, TN and NO_3 concentrations recorded in the subsequent winter. Nevertheless, no significant or rather week correlations between nutrients and time since fertilization, as well as tillage, were identified (Table 2). TP, TN and NO_3 concentrations were positively correlated with each other ($p \leq 0.01$, Table 2), but no significant correlations with TSS, rainfall and runoff were recorded (Table 2).

Mean annual TP export through runoff was 2.0 kg ha^{-1} (Fig. 6). P5 exported greater TP than P4 (0.4–6.5 kg ha^{-1} yr^{-1} vs 0.5–0.9 kg ha^{-1} yr^{-1}, $p < 0.05$) and slightly higher loads than P1 and P2 (0.4–3.7 kg ha^{-1} yr^{-1} and 0.6–3.4 kg ha^{-1} yr^{-1}) over the study period ($p \geq 0.05$). Mean annual TN export from the vineyard was 6.0 kg ha^{-1}, highlighting greater nitrogen than phosphorus losses (2.1–4.5 orders of magnitude). Mean annual NO_3 export was 0.4 kg ha^{-1} and comprised 4%–11% of dissolved TN exports. No significant difference between plots was identified in TN and NO_3 exports ($p > 0.05$).

Apart from great inter-annual differences on nutrient exports, significant seasonal differences were also noticed over the study period ($p \leq 0.05$; Fig. 6). Significant but rather week positive correlations were identified between nutrient exports and rainfall, as well as runoff ($p < 0.01$, Table 2).

Results from this study did not reveal significant correlations between nutrient exports and the number of days after fertilization ($p \geq 0.05$, Table 2). The number of days after tillage exhibited week negative correlations with TP and TN exports ($p < 0.01$, Table 2). Although tillage did not significantly influence NO_3 exports ($p \geq 0.05$, Table 2), during the greater winter 2013 rainfalls, they were 1.7 times greater in the relatively recent tilled P1 and P5 plots than the untilled P2 and P4 (Fig. 6c).

Nutrient exports displayed stronger significant positive correlations among each other than observed with nutrient concentrations, and significant correlations with TSS exports ($p < 0.01$, Table 2).

4. Discussion

4.1. Impact of tillage on runoff and sediment exports

Minimum tillage has been adopted to mitigate land degradation and led to runoff coefficients ranging from 11% to 19% over the study period. These values are lower than reported for conventional tilled vineyards in Madrid, Spain, with clay soils similar to São Lourenço (42%, Marques et al., 2009), but higher than those recorded in Italy for loamy harrowed and permanently grass covered inter-rows (9.4% and 8.3%, respectively; Napoli et al., 2017). According to García-Díaz et al. (2017b), slope does not have a relevant impact on runoff generation in vineyards with gentle slopes (< 15%), as is the case of the São

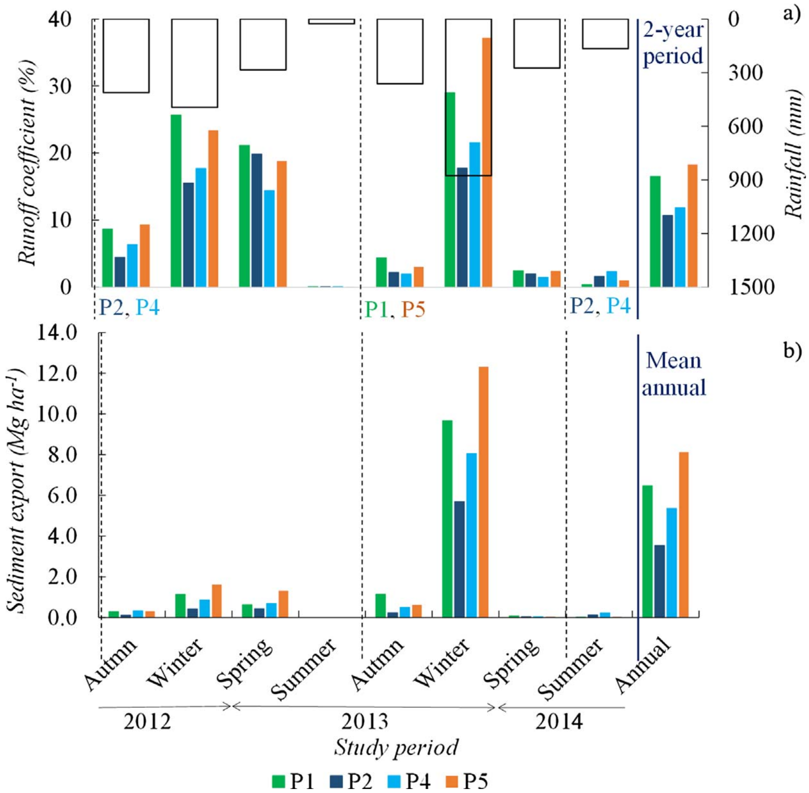

Fig. 4. Seasonal rainfall and runoff coefficient, and total runoff coefficient over the two years study (a); and, seasonal and mean annual sediment export (b) in each of the four runoff plots. Vertical dashed lines indicate dates of tillage.

Table 2
Spearman's rank correlation coefficients between sediment and nutrient concentrations as well as exports, rainfall, runoff and management practices ("–" indicate dependent variables; * and ** represent correlations with a 0.05 and 0.01 level of significance, respectively; n = 260).

	Concentrations (mg L^{-1})				Exports (g m^{-2})			
	TSS	TP	TN	NO_3	TSS	TP	TN	NO_3
TP (mg L^{-1})	0.396**							
TN (mg L^{-1})	0.300**	0.770**						
NO_3 (mg L^{-1})	0.132	0.421**	0.523**					
TSS (g m^{-2})	–	0.139	0.120	0.186*				
TP (g m^{-2})	0.190**	–	0.134	0.164	0.981**			
TN (g m^{-2})	0.209**	0.140	–	0.151	0.991**	0.991**		
NO_3 (g m^{-2})	0.187*	0.084	0.121	–	0.935**	0.935**	0.935**	
Rainfall (mm)	0.790**	0.256**	0.289**	0.123	0.220**	0.263**	0.284**	0.296**
Runoff (mm)	0.764**	0.0131	0.176*	0.015	0.272**	0.320**	0.330**	0.343**
N° of days after tillage	−0.283**	−0.231**	−0.141	−0.224**	−0.165**	−0.202**	−0.192**	−0.230
N° of days after manure application	0.077	−0.285*	−0.119	−0.029	0.026	−0.014	−0.009	0.018
N° of days after foliar fertilization	−0.064	−0.285*	−0.119	−0.029	−0.136	−0.181*	−0.174	−0.141

Lourenço vineyard.

Although runoff did not show significant differences between plots over the two years of study ($p < 0.05$), mean runoff was 1.5 times higher in once tilled plots (P1 and P5) than in twice tilled plots (P2 and P4), despite temporal variations linked with time since tillage (Fig. 3a). For example, P1 and P5 produced less runoff than P2 and P4 (0.3–1.2 folds) in storms occurring immediately after tillage (Fig. 3a). This is thought to be a consequence of the increase in surface water retention capacity, provided by enhanced soil roughness and infiltration capacity. Nevertheless, when depression storage capacity was surpassed after several rainfall winter events, runoff in P1 and P5 attained 7.0–23.6 folds of the runoff measured in P2 and P4. Previous studies in vineyards reported differences in runoff between tilled and non-tilled plots just after treatments, decreasing with time and rainfall (Raclot et al., 2009).

In the study site, however, when tillage was performed in spring 2014, P2 and P4 generated higher runoff than untilled P1 and P5 (2.4–3.3 folds), possibly due to greater rainfall interception by the extensive vegetation cover (Fig. 7a and b). Plot experiments elsewhere showed that natural vegetation cover can produce 20% less runoff than bare soils (Zhang et al., 2010) and different cover crops can reduce 25–45% of the runoff (Novara et al., 2011). However, based on current study, limited vegetation cover driven by water scarcity during summer seems to be less effective in preventing runoff (Fig. 7c) than surface roughness enhanced by tillage (Fig. 7d).

Runoff was mostly generated in winter, ranging from 15% to 40% of the rainfall, driven by larger and more frequent storms (Fig. 4a). In spring, relatively large runoff (up to 21.2%) was driven by the wettest antecedent weather conditions, as evidenced by the strong positive correlation between rainfall and runoff ($r = 0.822$, $p \leq 0.01$). Higher soil moisture resulting from previous storms may have led to increasingly connected pathways and, thus, flow generation, as reported by Masselink et al. (2016) and Rodrigo-Comino et al. (2016). Furthermore, high traffic machinery associated with 11–13 annual treatments (including fertilization and pesticides application) performed mainly in

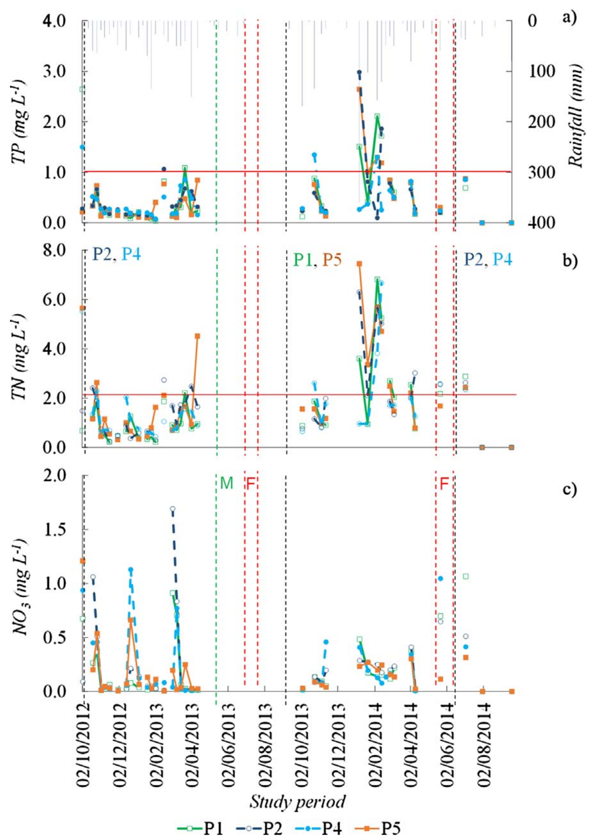

Fig. 5. Rainfall, total phosphorous (TP) (a), total nitrogen (TN) (b) and nitrate (NO_3) (c) losses in the four runoff plots, over the 2-year study (missing values are due to lack of samples). Vertical dashed lines represent tillage (grey), manure application (green, M) and foliar fertilization (red, F). Horizontal red lines represent Portuguese minimum surface water quality standards for total phosphorous. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

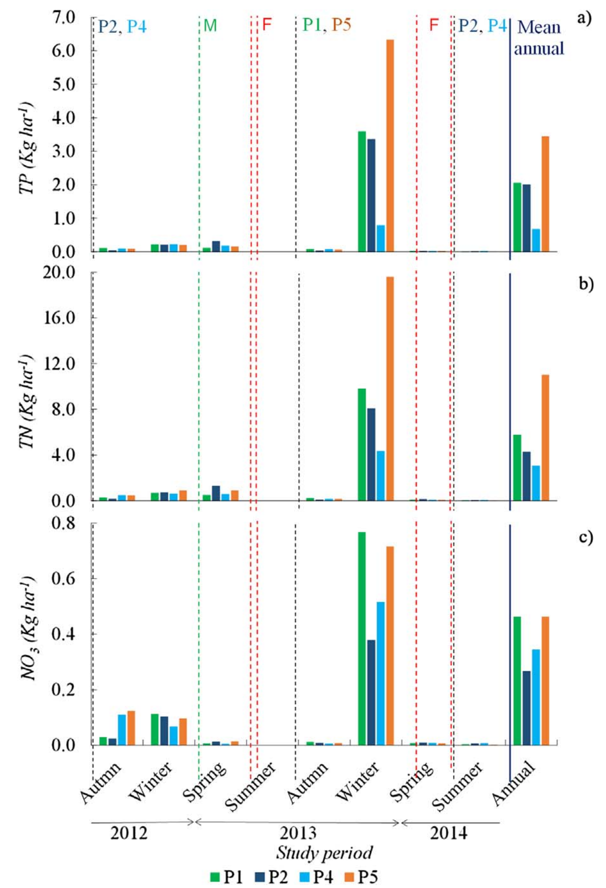

Fig. 6. Seasonal total phosphorous (TP) (a), total nitrogen (TN) (b) and nitrate (NO_3) (c) exports in the four runoff plots, over the study period. Vertical dashed lines represent tillage (grey), manure application (green, M) and foliar fertilization (red, F). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

spring, but also in summer, favour soil compaction and contribute to runoff generation (Fig. 7c), as widely reported (e.g. Rodrigo-Comino and Cerdà, 2018; Biddoccu et al., 2017). Hortonian overland flow was dominant in summer and autumn, leading to limited runoff coefficients (< 2% and 2%–9%, respectively). Over driest settings, mostly in summer, overland flow generation is favoured by surface crusting, which impeded infiltration (Kosmas et al., 1997; Napoli et al., 2017).

Erosion principally occurs in winter driven by high rainfall/runoff events (Fig. 4b), as evidenced by the strong positive correlation between runoff and TSS ($r = 0.764$, $p < 0.01$). Nevertheless, some of the highest sediment concentrations were recorded after tillage, even when low runoff was generated (Fig. 3c). In P2 and P4, sediment yields driven by 37 mm of rainfall (03/07/2014), occurring immediately after tillage, produced ~10% of the sediment export recorded over the two years. In P1 and P5, a 169 mm rainfall event that occurred after tillage (04/10/2013) led to sediment yields representing 19% of the total sediment exports. After tillage, a large amount of sediments is readily available, and easily detached by rainfall and transported through runoff. Runoff and soil erosion by tillage has been widely reported in vineyards (e.g. Ramos and Martínez-Casasnovas, 2006; Napoli et al., 2017). Nevertheless, the depletion of available soil particles during the first storms after tillage influence the following sediment exports (Fig. 3c).

Besides tillage, soil crust and vehicular traffic has been reported to enhance soil erosion (Kosmas et al., 1997; Boulal et al., 2011; Rodrigo-Comino and Cerdà, 2018), which may explain the relatively high TSS concentrations in summer 2014 (Fig. 3c).

Although vineyards managed under integrated production were expected to mitigate land degradation, mean soil losses ranged from 7.1 Mg ha^{-1} in 2012/2013 to 16.2 Mg ha^{-1} in 2013/2014, indicating moderate to moderately high erosion according to the Joint Research Centre classification (Eurostat, 2013). These erosion rates exceed the annual soil formation rates of 0.3–1.4 Mg ha^{-1} in Europe (Verheijen et al., 2009), and the tolerable soil losses (6 Mg ha^{-1}) proposed for deep and well-developed soils (OECD, 2008). Thus, erosion mitigation practices adopted under integrated production (i.e. minimum tillage and partial vegetation cover) are not enough to prevent land degradation. Although vegetation cover has been widely reported to prevent erosion (e.g. Rodrigo-Comino et al., 2016), the dry conditions of the Mediterranean region naturally reduce vegetation cover, enhancing the impact of the first autumn rainfalls (Ruiz Sinoga and Martinez-Murillo, 2009). Thus, other soil cover options may be more relevant to prevent land degradation in semi-arid regions, such as straw mulching (e.g. Prosdocimi et al., 2016) or pruning wastes (e.g. Keesstra et al., 2016). The latter also improves soil fertility (Mwango et al., 2016). These additional management practices to mitigate runoff and soil erosion may be even more relevant to mitigate climate change impacts. Although Serpa et al. (2015) foreseen decreasing streamflow for São Lourenço catchment, with almost 50% of vineyard cover, as a result of decreasing precipitation, foreseen shorter but intensive storms is expected to exacerbate land degradation in vineyards. Soil losses measured in the São Lourenço vineyards were in agreement with other studies performed in conventional Mediterranean vineyards. In the Douro region, Portugal, erosion from a vineyard-dominated watershed was estimated to be 12.2 Mg ha^{-1} yr^{-1} (Pacheco et al., 2014). In Spain, soil losses were reported to range from 0.04 to 11.5 Mg ha^{-1} yr^{-1} in the Anoia–Alt Penedès region (Ramos and Martínez-Casasnovas, 2006), from < 1 to 13.9 Mg ha^{-1} yr^{-1} in Barcelona (Ramos et al., 2015) and

Fig. 7. Differences in vegetation density between tilled (a) and untilled plots (b) in 12/04/2013, runoff generation in tractor wheels paths (c), and enhanced soil surface roughness provided by tilling activities.

to attain values of 7.9 $Mg\,ha^{-1}\,yr^{-1}$ in Madrid (Marques et al., 2009). In Italy, erosion records from conventional vineyards reached 11.2 $Mg\,ha^{-1}\,yr^{-1}$ in Piedmont (Biddoccu et al., 2016) and 88.7 $Mg\,ha^{-1}\,yr^{-1}$ in Sicily (Novara et al., 2011). In Spata, Greece, erosion records ranged from 0.7 to 4.6 $Mg\,ha^{-1}\,yr^{-1}$ (Kosmas et al., 1997). Based on 227 plot-measuring sites in Europe and in the Mediterranean, Maetens et al. (2012) revealed erosion rates from bare-soil vineyards to range from 10 to 20 $Mg\,ha^{-1}\,yr^{-1}$. These high erosion rates highlight the continuous soil degradation in vineyards, revealing that management practices linked to integrated production are not enough to revert this situation. Nevertheless integrated production seems to be part of the solution since Galati et al. (2015) estimated that the annual costs of soil erosion in Sicily (Italy) were about 3 times higher in conventionally tilled than in agro-sustainable vineyards (a difference of 1088 € ha^{-1}).

4.2. Impacts of integrated production on nutrient exports

Nutrients are essential for vine growth and wine production, but they are partially mobilized by runoff and lost from the vineyard. In São Lourenço, nutrient losses (TP, TN and NO_3) varied deeply over the study period (Fig. 5). Greater TP and TN concentrations were measured in winter, during highest rainfall events, as reported in similar studies (e.g. Ramos and Martínez-Casasnovas, 2006).

TP surpassed the minimum quality standards for surface waters in Portugal during 9–16% of the measurement periods. When considering the USEPA water quality criteria (0.1 $mg\,L^{-1}$ of phosphate in streams or flowing waters; USEPA, 1986), it became evident that 91–100% of the analysed runoff samples pose a great risk of eutrophication for surface waters. As for TN, and according to the criteria established by Grizzetti et al. (2011) for European standing waters, 35–50% and 35–56% of runoff samples from the four plots represent a high ($>$ 1.5 $mg\,L^{-1}$) to medium (0.5–1.5 $mg\,L^{-1}$) eutrophication risk, respectively. Although nutrient runoff may not reach the stream network or be diluted by streamflow, these results highlight the relevance of the vineyards as a diffuse source of pollution.

Lower dilution effect may also explain the higher NO_3 concentrations (up to 1.07–1.69 $mg\,L^{-1}$), usually associated with smaller rainfalls and runoff (Fig. 5c). Furthermore, some of the highest NO_3 concentrations were recorded after tillage, and may be linked to management practices. García-Díaz et al. (2017a) also reported higher concentrations of NO_3 in runoff from tilled vineyards.

Nitrates represented only 4%–11% of TN over the 2-years of study. This low fraction of NO_3 is thought to be a consequence of the (i) type of fertilization (Ramos et al., 2015), including inorganic foliar fertilizers and organic fertilizers (manure); and (ii) the high NO_3 solubility and susceptibility to leachate with rainfall (Fox et al., 2001). This contrasts with other Mediterranean vineyards, where NO_3 losses represent the main form of mineral nitrogen in runoff, since ammonium is usually adsorbed to organic-clay sediment particles (García-Díaz et al., 2017a).

The type of fertilizers and post-fertilization weather conditions may explain the lack of significant correlations between nutrient losses and

time since fertilization (mineral and organic) (Table 2). In fact, previous studies reported no direct linkages between nutrient losses and fertilization in vineyards, but rather with rainfall-runoff processes (Ramos and Martínez-Casasnovas, 2006; García-Ruiz, 2010; Napoli et al., 2017).

The absence of significant differences in nutrient losses recorded between plots ($p > 0.05$, Fig. 5), contradicts the findings of other authors which found lower nutrient losses in vineyards with spontaneous vegetation cover than in conventionally tilled vineyards (6 and 5 times less NO_3 and TN losses; García-Díaz et al.,2017). Likewise, Napoli et al. (2017) reported mean N and P losses 2.5 and 1.3 times greater in harrowed inter-row than grass covered vineyard plots. Nevertheless, the plots installed in São Lourenço display the impact of integrated production management practices, with all plots recording tilled and non-tilled cycles over the study period.

The relatively high nutrient concentration in the runoff from the São Lourenço vineyard, however, highlight the relevance to implement additional mitigation strategies, such as buffer strips (Novara et al., 2013; Ramos et al., 2015) and wetlands (Napoli et al., 2017), to control nutrient pollution from vineyards.

Mean annual losses were 0.5–3.6 kg ha^{-1} of TP and 1.3–10.8 kg ha^{-1} of TN (Fig. 6). These losses were lower than those reported in conventional vineyards. Napoli et al. (2017) reported annual N and P losses up to 4.5 kg ha^{-1} and 6.2 kg ha^{-1} in grassed plots, and up to 12.5 kg ha^{-1} and 5 kg ha^{-1} in harrowed plots, respectively, from a vineyard in Central Italy. For high intensity rainfall events (> 80–100 mm h^{-1}) in NE Spain, Ramos and Martínez-Casasnovas (2006) reported annual N and P losses by runoff to be 14.9 kg ha^{-1} and 11.5 kg ha^{-1}, respectively.

Fertilization provides considerable N and few P supplementation to the vineyard, considering (1) soil fertilization, based on manure composition (MADRP, 1997) and application rates (Table 1) (1.5 kg ha^{-1} of TN and 0.16 kg ha^{-1} of TP); and (2) foliar fertilization practices (2.0 kg ha^{-1} of TN and 0.2 kg ha^{-1} of TP), estimated from the technical recommendations provided by local farmers' association (APIBAIRRADA), regarding the type and chemical composition of foliar fertilizers and their application rates (Table 1). But a significant part is lost with runoff. Mean TP and TN losses over the 2-years of study were 12.7 and 3.6 times higher than the amount of fertilizers applied. These losses may be, however, underestimated since they are solely based on runoff exports and do not take into account losses by leaching or erosion processes. This hypothesis is corroborated by the fact that nutrients exports (TP and TN) were strongly correlated with TSS exports ($p < 0.01$). Other authors also reported greater correlation of N and P with transported sediments than with runoff volume (Napoli et al., 2017).

In the study site, the proportion of nutrient exports relatively to nutrient inputs by fertilization are higher than that reported for conventional vineyards. For example, Ramos and Martínez-Casasnovas (2006) indicated N and P exports by runoff represented respectively 6% and 26% of the annual N and P intakes. Zhang et al. (2010) also noticed that only 30–40% of the fertilizer applied in a Chinese vineyard is actually uptake by the plant.

An explanation for these findings could be the lower fertilization rates used in the São Lourenço when compared to conventional vineyards. Additionally, one could relate these results to the relatively wet conditions in the two study years, as these are likely to have promoted runoff and the associated sediment and nutrient losses. In fact, in Catalonia (Spain), García-Ruiz (2010) reported nutrient losses during a single extreme rainfall event (return period of 105 years) to represent 12.5% and 60.5% of the annual N and P application.

Although integrated production restricts the rate of fertilization to prevent environmental degradation, high nutrient losses occur, which may contribute to (i) a decline in surface water quality (Cerqueira et al., 2005) and damages to aquatic ecosystems (Moss, 2008); (ii) decrease in crop productivity (Verheijen et al., 2009); and (iii) high economical losses for grape producers. In NE Spain, the costs associated to N and P fertilization represented 2.4% and 1.2%, respectively, of the annual income from grape sales (Martínez-Casasnovas and Ramos, 2006). In addition, the price of N and P fertilizers has been increasing over the last years.

5. Conclusions

Integrated production implies the adoption of reduced soil tillage techniques (only once per year in each inter-row) and establishes limits to fertilization rates. Results from two years of measurements in São Lourenço vineyard, established in the Bairrada wine region, indicate relatively lower annual runoff (15%) and nutrient exports (0.5–3.6 kg ha^{-1} of TP, 1.3–10.8 kg ha^{-1} of TN and 0.1–0.6 kg ha^{-1} of NO_3) than those reported for conventional Mediterranean vineyards practicing intensive soil tillage (at least twice per year) and higher fertilization rates. High erosion rates, however, were measured (7.1–16.2 Mg ha^{-1} yr^{-1}), highlighting the unsustainability of vine culture.

Nevertheless, surface runoff is still an important pathway for sediment and nutrient transport. Mobilized N and P, particularly during wet periods, can reach high concentrations in runoff, surpassing the Portuguese surface water quality standards. Besides water pollution, nutrient losses reduce local soil fertility and may affect vine productivity, which represents economic losses to farmers.

Apart from seasonality, management practices, namely tillage and fertilization, can also strongly influence sediment and nutrient losses by runoff. Long-term measurements, however, are needed to fully assess the impact of integrated production on vineyards' sustainability.

Although vineyard integrated production in Portugal has been receiving governmental subsidies, these management system does not seem enough to prevent land and water quality degradation. Additional research and knowledge transfer from the scientific community to policy makers should be promoted, to improve the effectiveness of agro-environmental incentives.

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