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Long-term non-sustainable soil erosion rates and soil compaction in drip-irrigated citrus plantation in Eastern Iberian Peninsula

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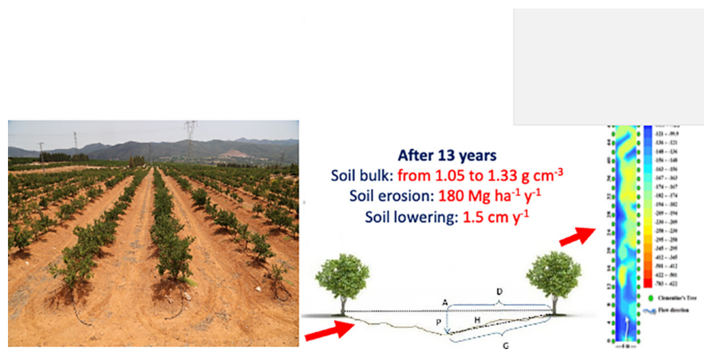
HIGHLIGHTS

- Soil bulk density increased from 1.05 to 1.33 g cm^{-3} in 13 years.
- Machinery passes increase soil compaction in the inter-row center till 1.43 g cm^{-3}.
- High soil losses were located in the center of the inter-row till 277 Mg ha^{-1} y^{-1}.
- New drip-irrigated plantations on slopes accelerate soil erosion.
- Long-term soil erosion measurements assess agriculture sustainability.

GRAPHICAL ABSTRACT



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ABSTRACT

Agriculture is known to commonly cause soil degradation. In the Mediterranean, soil erosion is widespread due to the millennia-old farming, and new drip-irrigated plantations on slopes, such as the citrus ones, accelerate the process of soil degradation. Until now, the published data about soil erosion in citrus orchards is based on short-term measurements. Long-term soil erosion measurements are needed to assess the sustainability of drip-irrigated citrus production and to design new strategies to control high soil erosion rates. The objective of this study is to assess long-term soil erosion rates in citrus plantations and report the changes in soil bulk density as indicators of land degradation. We applied ISUM (Improved Stock-Unearthing Method) to 67 paired trees in an inter-row of 134 m (802 m^2 plot) with 4080 measurements to determine the changes in soil topography from the plantation (2007) till 2020. Soil core samples (469) were collected (0–6 cm depth) to determine the soil bulk density at the time of plantation (2007) and in 2020. The results demonstrate an increase in soil bulk density from 1.05 g cm^{-3} to 1.33 g cm^{-3}. Changes in soil bulk density were higher in the center of the row as a result of compaction due to passing machinery. Soil erosion was calculated to be 180 Mg ha^{-1} y^{-1} due to a mean soil lowering of 1.5 cm yearly. The highest soil losses were found in the center of the inter-row and the lowest underneath the trees. The extreme soil erosion rates measured in new drip-irrigated citrus plantations are due to soil lowering in the center of the inter-row and in the lower inter-row position where the incision reached 80 cm in 13 years. The whole field showed a lowering of the soil topography due to extreme soil erosion and no net sedimentation within the plantation. The results show the urgent need for soil erosion control strategies to avoid soil degradation, loss of crop production, and damages to off-site infrastructures.

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1. Introduction

The fate of life on Earth depends on the health and diversity of the soil system (Rodrigo-Comino et al., 2020a; Kopittke et al., 2019). Soil is a filter for the hydrological cycle and contributes to all the biogeochemical cycles in the Planet (Totsche et al., 2010; Keesstra et al., 2012a). Soils hold fauna, plants, and fungi that interact to create a unique system that provide humans with water, food, and stable ecosystems (Lavelle et al., 1992; Chary et al., 2008; Keesstra et al., 2012b). Soil also affects the current and future climate and contributes to avoiding extreme events that will end in floods (Melillo et al., 2017; Kramer and Chadwick, 2018; Novara et al., 2019a, 2019b; Borrelli et al., 2020). Soils preserve our heritage and contribute to a diverse landscape, and soils sustain human and ecosystem health (Amato et al., 2017; Sanderman et al., 2017; Brevik et al., 2019). Although soils are key to the sustainability of humankind, soils are threatened by human activities that result in soil degradation, and as a consequence our mismanagement in soil protection risks resources, services, and goods (Banwart, 2011; Rodrigo-Comino et al., 2020a; Tibbett et al., 2020).

The human activities that alter the soil functioning are mainly agriculture, forestry, mining, grazing, and soil sealing by the urban expansion and infrastructures such as roads, railways, and airports. Forestry activities disturb soils due to the compaction during harvest such as Busse et al. (2021) found in California mixed-conifer forest after 20 years due to the non-recovery of the previous soil properties and highlighted the importance of the O horizon to long-term soil health. Mining induces the disturbance or the disappearance of the soil, but always produces on-site and off-site impacts such as Fiket et al. (2020) found in coal mines, where they claim for an assessment of the anthropogenic activities in historical mining areas. Grazing was very intense in the past and still creates changes in the soil system due to overgrazing (Antoneli et al., 2020; Lozano Fondón et al., 2020). Infrastructures cause the sealing of the soils due to urban development and road expansion in the world (Hategekimana et al., 2020).

Within all the human impacts described above, agriculture is the one that induced a more dramatic change in the soil system and the hydrological cycle (Cerdà et al., 2021a). Agriculture removed the natural vegetation, plow the soils, and introduced irrigation and as a consequence of the abuse of chemical fertilizers provoke soil pollution, soil structure degradation, and organic matter reduction and soil compaction (Novara et al., 2020; Vilček et al., 2020). The long-term impact of agriculture induces an increase in soil erosion rates all over the world. This is a widely accepted fact that has been confirmed in the last century within scientific research. High soil erosion rates were registered in cereals crops (Thorne et al., 2003; Li et al., 2007; Chalise et al., 2020). Recently, the largest soil erosion rates were found in groves and vineyards due to the mechanization and the lack of plant covers. Baiamonte et al. (2019) researched soil erosion processes and rates in Sicilian vineyards, Telak and Bogunovic (2020) in Central Croatia vineyards; Barrena-González et al. (2020a) in the vineyards of Extremadura, Keesstra et al. (2016) in the apricot's fields in Spain, Telak et al. (2021) on hazelnut orchards in Croatia, Fraga et al. (2021) in olive orchards, Barrena-González et al. (2020a, 2020b) in chestnut tree plantations and Rodrigo-Comino et al. (2020b) on persimmon plantations. The regional and experimental findings mentioned above are confirmed by the State-of-the-Art by Rodrigo-Comino (2018) and Novara et al. (2021) and by the overviews of Nearing et al. (2017), Borrelli et al. (2020), and Panagos et al. (2020). Within the world agriculture land, the Mediterranean climatic area shows extreme values due to the rugged terrain, the intense rainfall intensities, and long human use of the soils. Citrus crops are a widespread crop in the western Mediterranean basin. However, in the last decades, new citrus plantations are appearing on sloping areas irrigated by drip-irrigation that do not need a terraced landscape as before. These plantations are characterized by highly mechanized management, a very high abuse of herbicide, bare soils, and steep, long slopes to facilitate the use of heavy machinery. Citrus has not been seen until recently as a crop that induces high erosion rates, as most of the studies were developed on vineyards and olives plantations, the ones are considered the traditional Mediterranean crops (Rodrigo-Comino et al., 2018a, 2018b; Novara et al., 2021).

Citrus plantations are found in different countries, but Spain and China are the only regions that devoted research efforts to assess the effect on soil erosion. In China, the research on soil erosion in citrus plantations has shown high erosion rates. Recently, Duan et al. (2020) showed that soil erosion under extreme rainfall events is very high in southern China and the use of groundcover was the solution to control the loss of water and soil. Similar findings were found by Zhang et al. (2020). They confirmed previous investigations such as the ones of Liu et al. (2012), Tian et al. (2003), Jianjun et al. (2017), and Mo et al. (2019). In Spain, soil erosion rates were found to be high also. Cerdà et al. (2018), Keesstra et al. (2019), Cerdà et al. (2019), and Rodrigo-Comino et al. (2020b) measured similar high erosion rates, which can be seen as evidence of non-sustainable management.

The published data about soil erosion in citrus orchards shown above is based on rainfall simulation experiments and plot assessment. They show short-term measurements. The long-term impact of soil erosion in citrus plantations will contribute to a better understanding of the role of soil erosion in the sustainability of citrus production and plan new strategies to control the high soil erosion rates. The objective of this research is to assess the long-term soil erosion rates in citrus plantations and report the changes in soil bulk density as an indicator of soil change over the 13 years of research. This will shed light on the process of land degradation induced by the new highly mechanized citrus plantation in sloping terrain.

2. Materials and methods

2.1. Study area

The Peiró-Camaró farm was selected as a representative farm of new sloping, drip-irrigated citrus plantations and used as a living laboratory along the two decades of the experimental approach. The samplings were planted in 2007 after a complete reshuffle of the fields with the elimination of the pre-existing terraces, deep plowing, and new ridges to plant the citrus trees. The farm is located in the municipality of Canals (Supplementary material 1). Peiró-Camaró farm is positioned on a slope that is covered with citrus plantations since the 1960s. Soil is classified as Xerorthent (WRB, 2015) and has a soil texture of 22% clay, 31% silt, and 47% sand. Stone content in the soil was 0.76% and at the soil surface moved from 1.05% in 2007 till 2.65% in 2020. The climate of the Canyoles river basin is characterized by a typical Mediterranean summer drougth, with a mean annual rainfal of 550 mm. The mean annual temperature is 16.2 °C with hot summers (25 °C) and mild winters (10 °C).

The clementine variety planted was Tangold (Tangerine Gold) with also a given name by farmers as "Tango". This citrus is officially named "Gold Nugget Tangerine" and is a variety of *Citrus reticulata* L. var. also referred to as *Citrus tangerina* L. The farm covers an area of 65,347 m^2 and is all planted with the Tangerine Gold variety and surrounded by other citrus plantations with varieties such as Valencia late and Navel lane late. The plantation is made at a distribution of trees of 6 m × 2 m. The farmer developed a furrow and ridge system and located the trees in the ridge (Supplementary material 2). The field is drip-irrigated (two pipes per line of trees with drips each 1 m). Irrigation is applied using drips during the dry periods, mainly in summer, although in other seasons if the rain is not enough and irrigation necessary also takes place. The management of the cover is by herbicides (Glyphosate (*N*-phosphonomethyl)glycine) applied once weeds emerge. The farm use to have a bare soil as each month the herbicide is sprayed to avoid any weed. The objective of the farmers is to keep the soil bare. Inorganic fertilizers are applied with drip irrigation (NPK, 1.2 Mg ha^{-1} y^{-1}). Iron chelates are also applied due to the high soil calcium carbonate content. A Lamborghini tractor (674-70SPRINT) with front and rear wheels tires of 320–24 and 480–30, respectively, was used for the plantation and the

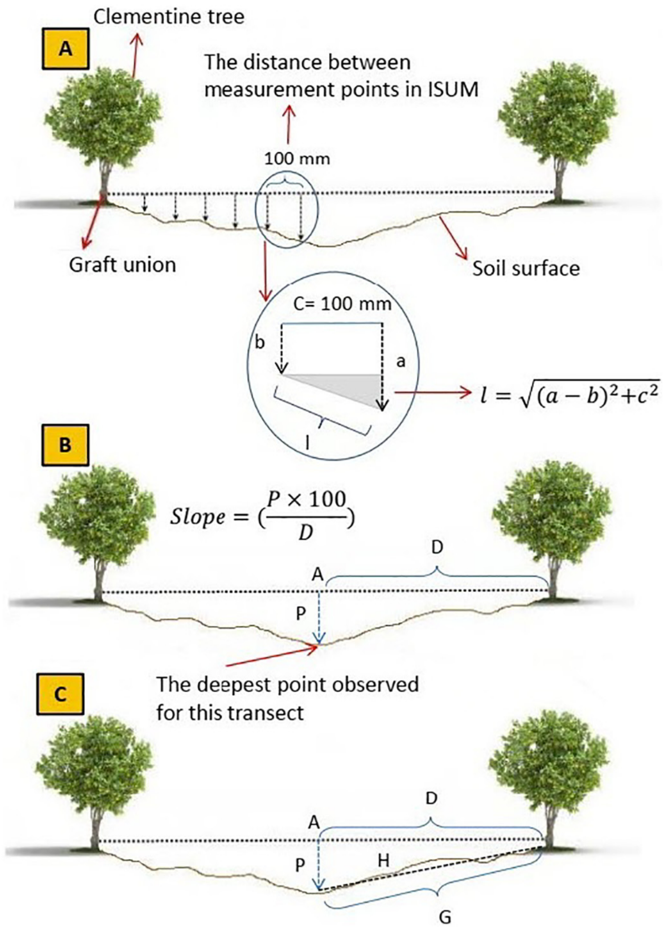

Fig. 1. View of the strategy to take samples for the core method (soil properties) and the ISUM measurements. The core samples were located at 0, 100, 200, 300, 400, 500, and 600 cm from the tree and the ISUM sampling each 10 cm.

works on the farm. The wheelbase of the tractor is 2056 mm, and a total weight of 2720 kg. This tractor is used to spray chemicals and to chip pruned branches. The pruned branches are chopped immediately after the pruning at the end of March.

2.2. Topographical analysis through ISUM

The use of topographical measurements with ISUM is based on a survey of the topography of the plot done in 2020 (June) and the original topography during the plantation of the field in April 2007. The original topography is calculated utilizing the craft of the trees, which is done at 7 cm above the surface of the soil with a ruler (1 mm accuracy). For the ISUM (Improved Stock Unearthing Method) measurements we selected a representative inter-row line of 67 trees (distance between trees of 2 m), with is a total of 134 m surveyed. The distance between rows of trees is 6 m with a plot of $804 m^2$. For each tangerine tree, we marked the graft union following the guidelines published by Rodrigo-Comino and Cerdà (2018). *A*1 mm thick nylon rope (700 mm length) was fastened from tree to tree (see Fig. 1) at the graft's height. The height of the rope to the soil surface was measured each 10 cm intervals along the rope. This way, 60 measurement points were collected in each sampling from the tree (1 measurement) to tree (1 measurement) and between trees (58 measurements). A total of 4020 measurements (67 pairs of trees x 60 measurement points between trees) were measured, which is an average of 5 measurements per m^2 (1 sampling point per 0.2 m^2). Following the methodology of Rodrigo-Comino and Cerdà (2018) and their use in other publications in Persimmon (Bayat et al., 2019), Saturn Peaches (Cerdà et al., 2020), and Orange plantations (Rodrigo-Comino et al., 2020c) the selected inter-line space was surveyed to determine the soil bulk density that will allow transforming the topographical changes in soil erosion and soil redistribution maps.

After personal communication with the farmers of the region, the farmers confirmed that the planted trees had a uniform original height of the graft union, which was therefore assumed uniform for all trees at 7 cm. Topographical measurement using ISUM was carried out in June 2020, when no works are carried out in the field. Upon the measurements, a topographical map was created in ArcGIS 10.3 through interpolation of measured points for each plot.

2.3. Soil properties

Soil bulk density samples were taken at intervals 0, 100, 200, 300, 400, 500, and 600 cm between the trees at a depth between 0 and 6 cm. The core sampling method was used and a total of 448 samples were collected (0.56 samples per m^2). Fig. 1 illustrates the sampling positions for ISUM and core samples for organic matter and bulk density measurements. Soil core samples were collected using metal rings (6 cm diameter and 6 cm depth). After drying the samples in an oven (at 105 °C for 24 h), soil dry weight was calculated and then soil bulk density was calculated for each sample using soil volume (Moradi et al., 2020). The measurements of the soil properties were done in 2007 during the plantation and in 2020. This allows us to calculate the changes in soil bulk density and soil erosion.

2.4. Soil erosion

To calculate the soil erosion at the studied plot, the Surface Volume tool of ArcGIS 10.3 was used to determine the changes in the topography. This geoprocessing tool represents the volume of a surface above (original topography when the trees were planted 13 years before the measurement) or below (topography during the sampling period) a given reference such as previously applied (Cerdà et al., 2021b). In this study, we applied Eq. (1) (Paroissien et al., 2010) to calculate soil erosion and sediment accumulation rates *EV* in Mg ha^{-1} yr^{-1}:

$$EV = \frac{V \times BD_S}{A \times T} \quad (1)$$

Table 1
Descriptive statistics. Soil bulk density (g cm^{-3}) in 2007 and 2020 and the differences between 2020 and 2007 measurements.

Sample no	Distance (cm)	2007			2020			2020–2007		
		Average	STD	CV (%)	Average	STD	CV (%)	Average	STD	CV (%)
1	0	1.05	0.03	2.84	1.26	0.03	2.45	0.21	0.04	18.72
2	100	1.05	0.02	2.13	1.31	0.02	1.73	0.26	0.04	14.42
3	200	1.04	0.03	3.07	1.37	0.01	1.04	0.32	0.03	10.73
4	300	1.05	0.03	2.74	1.43	0.01	0.97	0.38	0.03	8.51
5	400	1.05	0.03	2.65	1.37	0.01	0.81	0.32	0.03	9.63
6	500	1.05	0.02	2.33	1.31	0.02	1.49	0.26	0.03	12.39
7	600	1.06	0.02	2.18	1.26	0.02	1.84	0.20	0.03	16.01
	Average	1.05	0.03	2.56	1.33	0.02	1.47	0.28	0.03	12.92

where V is the soil mobilized (volume) calculated from the topography in 2007 and 2020, BDs is the soil bulk density measured with the core method, A is the total area of the site, and T is the time since plantation (13 years).

2.5. Statistical analysis

Descriptive statistics (median, standard deviation, mean, maximum, minimum) were applied to correlate between the derived bulk density and ISUM maps. We calculated them and the coefficient of variation. Spatial correlation analysis was conducted in ArcGIS 10.3 using the Band Collection Statistics. This tool estimates the correlation coefficient $Corr_{ij}$ that explains the relationship between the two raster maps i and j using:

$$Corr_{ij} = \frac{Cov_{ij}}{\delta_i \delta_j} \quad (2)$$

where standard deviations of raster maps are defined by δ_i and δ_j, and Cov_{ij} is the covariance matrix between raster maps (*i* and *j*) defined by:

$$Cov_{ij} = \sum_{K=1}^{N} \frac{(Z_{ik} - \mu_i) - \left(Z_{jk} - \mu_j\right)}{N-1} \quad (3)$$

where *N* is the total number of cells in each raster map, Z_k is defined as a particular cell value of raster map i or j, and μ is the mean value of each raster map. Correlation values change between +1 to −1, so that positive values denote a direct relationship between the two raster maps, negative values denote inverse correlation, and independence between them is denoted by zero.

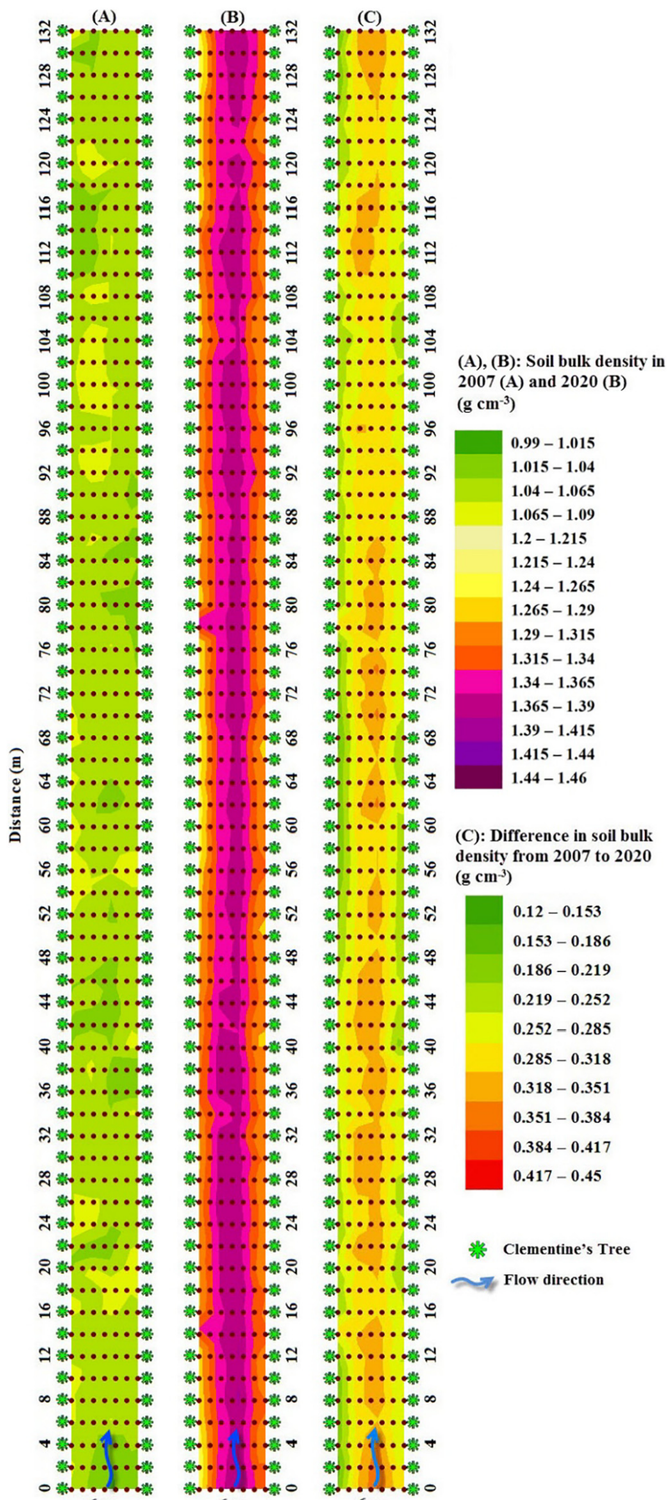

Fig. 2. Spatial distribution of the soil bulk density measured by ring sampling in 2007 (A) and 2020 (B) and difference 2020–2007 (C) at 0–6 cm depth.

3. Results

3.1. Soil bulk density

Soil bulk density was found to be 1.05 g cm^{-3} on average in 2007 after the plowing of the fields and the ridge construction. The standard deviation was 0.03 with low variability. The spatial distribution (Table 1; Fig. 2) shows no patterns. In 2020, on the contrary, there was a clear pattern of bulk density distribution with the highest bulk density in the center of the inter-row and with the lowest values in the areas underneath the trees (Fig. 2). After thirteen years, the bulk density increased from 1.05 g cm^{-3} till 1.33 g cm^{-3} on average for the whole plot, but with values that were evenly distributed in 2007 and unevenly distributed in 2020, when the areas under the trees shown values of 1.26 g cm^{-3}, meanwhile the center of the furrow (inter-row) reached 1.43 g cm^{-3}. The increase in soil bulk density reached 0.28 g cm^{-3} in 13 years and the main increase was found in the center of the inter-row with an increase of 0.38 g cm^{-3}, and the lowest in the ridge underneath the trees with 0.20–0.21 g cm^{-3} of increase from 2007 till 2020. (See Table 2.)

The increase in soil bulk density from 2007 till 2020 was on average 20.0, 24.8, 30.8, 36.2, 30.1, 24.7 and 18.9% for the positions 0, 100, 200, 300, 400, 500 and 600 cm from the tree. This informs us that the increase in soil bulk density under the tree was lower than in the centre of the row. The mean annual increase in soil bulk density was 0.23 g m^{-3}. This was an average increase of 1.1% yearly. Fig. 2 shows the dramatic change in the whole plot, with all the sampling points with an increase in bulk density. Fig. 2 confirms that the largest changes in soil bulk density are found in the centre of the row.

Table 2
Descriptive statistics of ISUM data. Changes in soil topography (mm) from 2007 till 2020.

ISUM data set	2007–2020
Sample size	4087
Minimum (mm)	−783
Maximum (mm)	−35
Coefficient of variation (%)	57.11
Mean (mm)	−194.14
Total range (mm)	748
Median (mm)	−175
Standard deviation (mm)	110.88

Table 3
Descriptive statistics. Changes in soil topography (mm) from 2007 till 2020 at different position along the row.

Sample no	Distance (cm)	2007–2020		
		Average	STD	CV (%)
1–10	0–100	−159.00	54.60	34.34
11–20	110–200	−206.51	54.30	26.30
21–30	210–300	−302.46	164.19	54.28
31–40	310–400	−236.23	115.09	48.72
41–50	410–500	−159.20	48.27	30.32
51–60	510–600	−104.95	45.21	43.08
	Average	−194.73	80.28	39.51

3.2. Soil topographical changes

The data from the topographical measurements with ISUM show a lowering of the height of the original soil surface in 2007. The values ranged from 783 mm to 35 mm with a mean value of 194 mm. An average 15 mm of soil lowering each year of the 13 years of study were recorded. The spatial variability of the topographical variation shows that the upper plot area revealed lower soil lowering (0–58 m), meanwhile the lower part presents higher lowering. The threshold is found at 58–60 m (out of 134 m) from the upper part of the plot. The upper part showed values that are uneven in the change of topography, meanwhile the lower part of the plot (from 60 till 132 m) presents values that reach more than 500 mm. Another pattern of the soil topography variation is the high lowering of the soil in the center of the inter-row where the highest changes were found. The left part of the row (North) has reduced changes in topography in comparison to the right part (South).

The largest soil topographical changes were found in the centre of the inter-row, and the lowest underneath of the trees such is shown in Table 3. The soil lowering was 104.95 and 159.00 mm below the trees for the left and right tree lines (1 m from the trees). On the contrary, in the two meters located in the centre of the inter-row the values are 302.5 and 236.2 mm of soil lowering. (See Table 4.)

3.3. Soil erosion

Average soil erosion amounted 155.87 m^3 in the studied plot. All the sampling points showed a lowering of the soil level and then no accumulation areas were measured. The total detached soil and soil erosion in 13 years was 180 Mg ha^{-1} y^{-1} if the soil erosion rate is calculated with the average value of the bulk density of 2007 and 2020 assessment. The spatial variability also showed that there is an uneven distribution of the soil detachment as the upper part of the plot showed lower soil erosion rates than the lower one, where the higher average soil erosion rates are found and where the highest soil erosion rates are measured in the centre of the inter-row. The lowest soil erosion rates are found in the upper part of the plots with values around 100 Mg ha^{-1} y^{-1}, meanwhile in the lower area of the plot the values can reach 700 Mg ha^{-1} y^{-1}.

Table 4
Comparison of soil accumulation, soil detachment and total soil loss calculated using ISUM measurements and Bd for 2007 (a), 2020 (b) and average of 2007 and 2020 (c) during 13 years after tree establisment.

Parameters	m^3	Mg ha^{-1} yr^{-1}		
		a	b	c
Soil accumulation	0	0	0	0
Soil detachment	155.87	158.95	201.34	180.147
Total soil erosion	155.87	158.95	201.34	180.147

The distribution of soil losses can be seen in Fig. 4. We calculated the soil erosion rates based on the soil bulk density of 2007 and 2020, or the average of both measurements. The three maps generated confirm that the soil erosion rates are very high and that there are no areas with sedimentation, which demonstrate that the soil detachment and transport is very efficient. The soil losses measured along the 13 years of the experiment range from 28 to 801 Mg ha^{-1} y^{-1}, and no sedimentation areas were found within the study plot.

The largest soil erosion rates are found in the lower center part of the inter-row where the mean values show values of 276.87 and 216.24 Mg ha^{-1} y^{-1} for the area of 2 m located in the centre of the row (Table 5). The area below the trees (1 m) reached values of 145.55 and 96.07 Mg ha^{-1} y^{-1}. Another pattern found in Fig. 3 demonstrate that the lowest part of the plot shows higher soil erosion rates (Table 5). For the 2 m located in the centre of the row the soil losses were 148.65 and 137.34 Mg ha^{-1} y^{-1} from 0 to 58 m in the upper plot position and increased till 380.83 and 280.22 Mg ha^{-1} y^{-1} in the lower part (60–134 m). (See Table 6.)

4. Discussion

The measurements at the Peiró-Camaró study site indicate extreme soil erosion rates that are found due to the bare soil conditions, soil compaction due to the passage of heavy machinery in the centre of the inter-row, and sloping terrain. The long-term soil erosion rates in citrus plantations clearly demonstrates the need to assess the sustainability of citrus faming in different regions of the world and to develop and enhance suitable soil managements to reduce the soil losses.

4.1. Soil compaction. Causes and implications

Soil bulk density increased in 27% from 2007 till 2020 at the Peiró Camaró experimental farm. The causes are the use of heavy machinery, the lack of a vegetation cover as a consequence of the abuse of herbicides, the loss of the upper soil layers due to the erosion, and the exposition of the deeper soil layers, that always have a higher soil bulk density. Glyphosate is applied once some weeds are found as the objective is to have a bare soil the whole year. There is little information in the scientific literature about the impact of herbicides on soil compaction. And only recent research (Cerdà et al., 2021b) found the overall compaction of soils under herbicides in flood

Table 5
Soil erosion at different positions within plot studied at the Peiró-Camaró research sit.

Sample no	Distance (cm)	0–58 m			60–132 m			0–132 m		
		Average	STD	CV (%)	Average	STD	CV (%)	Average	STD	CV (%)
1–10	0–100	−140.38	46.02	32.78	−149.74	52.60	35.13	−145.55	49.98	34.34
11–20	110–200	−175.74	35.73	20.33	−199.81	56.39	28.22	−189.03	49.71	26.30
21–30	210–300	−148.65	52.17	35.10	−380.83	120.66	31.68	−276.87	150.29	54.28
31–40	310–400	−137.34	40.83	29.73	−280.22	98.01	34.98	−216.24	105.35	48.72
41–50	410–500	−155.06	43.66	28.16	−138.17	43.14	31.23	−145.73	44.18	30.32
51–60	510–600	−103.63	45.81	44.21	−89.94	36.28	40.34	−96.07	41.39	43.08
	Average	−143.47	44.04	31.72	−206.45	67.85	33.60	−178.25	73.48	39.51

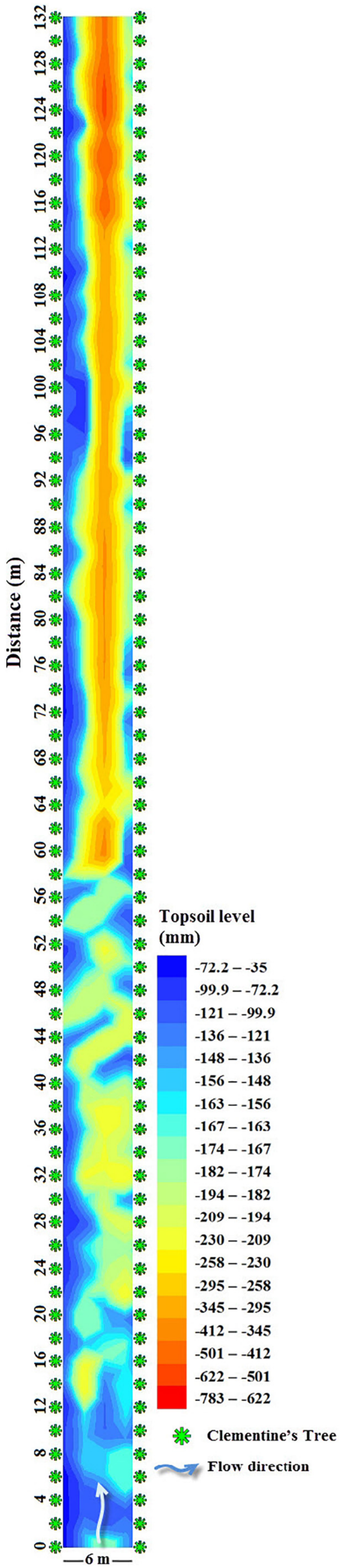

Fig. 3. Topsoil levels data obtained using ISUM in 2020 after the planting of the trees in 2007.

irrigated land; where all soil lowering can be considered due to soil compaction. The drip-irrigated orchard studied here showed an increase in soil bulk density at 0–6 cm of depth. Oliveira and Merwin (2001) measured after 8 years an increase of soil compaction in the Glyphosate and Paraquat treated plots in an orchard in New York in comparison with the mulch covered plots. Most of the previous research focused on other impacts of herbicides, such as the organic soil layer thickness and the earthworm richness (Garcia-Perez et al. (2020), invertebrates (Niemeyer et al., 2018) or soil microbial community (García-Delgado et al., 2018; Meena et al., 2020).

The lack of vegetation induces two main impacts on the soil that results in soil compaction of the upper soil layers. Bare soils are affected by raindrop impact and the formation of crusts, which induce soil compaction (Zhang et al., 2019), and the lack of vegetation (roots and litter) induces a consolidation of the soil. The scientific literature mainly focusses on how soil compaction affects the vegetation (Wang et al., 2019), although the compaction of the soil is often due to the lack of vegetation (Muhandiram et al., 2020).

The second cause that contributes to the soil compaction is the passage of heavy machinery, as is widely studied in the scientific literature. Keller et al. (2019) inform about the impact that soil compaction provokes in the soil system and Shah et al. (2017) reviewed how soil health and crop productivity are affected by the increase in soil bulk density. At the Peiró-Camaró experimental station, the 2 m located in the centre of the inter-row shows a higher soil bulk density due to the machinery compaction. Fig. 4 shows the impact that creates based on our measurements with ISUM and Fig. 5 shows a view of the impact of the recent passage of a tractor.

Soil bulk density increased in the research due to the loss of the upper soil layers. The soil detachment is the third cause that induced a 27% increase in soil bulk density due to the removal of the upper soil layer and the exposition of deeper soil layers that show higher soil compaction values. The fact that all the 4080 sampling points show a soil lowering informs about the intensity of the soil erosion that removes the upper layers and exposes to the surface deeper soil horizons that show higher soil bulk density (Aitkenhead and Coull, 2020). The soil surface layer that was present in 2007 has been removed by the surface wash due to water erosion and deep layers are now found in the surface.

4.2. Soil erosion in citrus plantations as a man-made accelerated process

Within the land degradation issues, soil erosion is characterized as a man-made accelerated process. This is very relevant in European countries where 24% of the land has unsustainable soil water erosion rates following the assessment of Panagos et al. (2015). With the ambition of the EU with the recently adopted Green Deal and soil Mission Board (Veerman et al., 2020) to have 75% of all European soils under sustainable management, the call for sustainable agricultural management practices is ever louder. But also, in other part of the world high erosion rates are found. Gharibreza et al. (2021) found in the Central North of Iran, that tea plantations reach 17.06 Mg ha^{-1} y^{-1} when measured with the ^{137}Cs technique and 20.4 Mg ha^{-1} y^{-1} with the RUSLE model. The deforestation of the area 50 years ago resulted in high sediment delivery and the degradation of the soils that must be restored due to the lost soil quality. Many parts of China also show high erosion rates such as Li et al. (2020) measured with the ^{137}Cs technique in Southwest China, where an average soil erosion rate of 6.32 Mg ha^{-1} y^{-1} was measured in a Karstic area. Barrena-González et al. (2020a, 2020b) measured soil erosion rates of 17.4 Mg ha^{-1} y^{-1} with RUSLE and 45.7 Mg ha^{-1} y^{-1} with ISUM in the vineyards of Extremadura in the

Table 6
Soil lowering by soil compaction, soil losses and total (soil compaction plus soil losses).

Sample no	Distance (cm)	Compaction (mm)			Soil losses (mm)			Total (mm)		
		Average	STD	CV (%)	Average	STD	CV (%)	Average	STD	CV (%)
1–10	0–100	13.86	2.22	16.04	145.14	53.97	37.19	159.00	54.60	34.34
11–20	110–200	16.93	2.36	13.96	189.58	54.08	28.53	206.51	54.30	26.30
21–30	210–300	19.99	2.33	11.63	282.47	164.42	58.21	302.46	164.19	54.28
31–40	310–400	19.35	2.25	11.60	216.88	114.89	52.97	236.23	115.09	48.72
41–50	410–500	16.41	2.01	12.26	142.79	47.96	33.58	159.20	48.27	30.32
51–60	510–600	13.46	2.13	15.80	91.49	44.68	48.84	104.95	45.21	43.08
	Average	16.67	2.22	13.55	178.06	80	43.22	194.73	80.28	39.51

Iberian Peninsula. They confirmed the acceleration of soil erosion rates found by Rodrigo-Comino et al. (2019) when they claimed that the use of ISUM demonstrated that after 20 years the soil erosion rates reached a rate of 71.2 Mg ha^{-1} y^{-1}. In Nepal, Chalise and Kumar (2020) found that the agricultural expansion resulted in an increase in soil erosion rates from 5.35 to 6.03 Mg ha^{-1} y^{-1} from 1995 till 2015. Most of the agriculture land of the world show non-sustainable soil losses. The high erosion rates induced by tillage were found in Belgium, (Ryken et al., 2018), Borneo (Vijith et al., 2018), India (Thomas et al., 2018), Brazil (Antoneli et al., 2018), Uganda (Karamage et al., 2017) and Sicily (Novara et al., 2019a, 2019b).

The data collected in the Peiró-Camaró farm demonstrated that the soil erosion rates are very high as they reach values as much as 180 Mg ha^{-1} y^{-1}1 on average, with extreme values that reach 800 Mg ha^{-1} y^{-1}. The data showed that all their study plots lost soil, which means that all the sediments detached are transported off the farm. Also, in Valencia, high soil erosion rates in the citrus farms are widespread (Keesstra et al., 2019). Especially in the farms where herbicides are used to avoids any cover of weeds that could reduce soil losses through higher infiltration rates and surface runoff reducing the overland flow and associated erosion. Supplementary material 3 shows six views of the citrus plantations, where weeds are prohibited to growth with the use of glyphosate.

Our findings at the experimental site and the literature review confirms that land use and climate changes will impact in an increase in the global soil erosion by water (Borrelli et al., 2020) and this claim for an immediate change in the soil management to achieve a sustainable land management in agriculture land.

4.3. The need of a sustainable citrus cropping

Accelerated soil losses in agricultural land are found under different climate zones of the Planet (García-Ruiz et al., 2015). This is especially relevant in Mediterranean type ecosystems where soil erosion has been threatening soil sustainability, and with that food security, since ancient times (Poesen and Hooke, 1997; Butzer, 2005). Over the last decades, the traditional tillage system used in the Mediterranean shifted to a highly mechanized with intensive use of herbicides. In the newly constructed drip-irrigated mechanized citrus orchards on sloping terrain, the impact of this new herbicide management resulted in an increase of soil bulk density and triggered high erosion rates. In the traditional system, flood irrigation was used that had as a side effect the need for a flat terrain. The implementation of drip irrigation has allowed the irrigated agriculture such as citrus plantations to move up the hillslopes without the use of terraces. Therefore, the plantations are on sloping terrain without any contour breaks, that are kept bare of vegetation using herbicides. This landscape is highly vulnerable for land degradation and has similar erosion characteristics as are commonly found in badlands and gullies. At the Peiró-Camaró experimental farm 180 Mg ha^{-1} y^{-1} was measured, and similar measurements were registered in the badland landscapes that are considered the landscapes with the highest soil losses. Llena et al. (2020) found high erosion rates in badlands in the Iberian Peninsula; Higuchi et al. (2020) in Taiwan, Dill et al. (2020) in Colombia and Juez and Nadal-Romero (2021) in the Pyrenees. Although badlands and gully landscapes are natural landscapes the scientific literature focusses on the high erosion rates. On the contrary, citrus plantations are not an issue although the soil losses found in them are similarly huge. The lack of the sustainability of these citrus plantations should be made aware the society, policymakers and farmers. We claim here that there is a need to develop proper management strategies to stop the soil losses and achieve a sustainable soil erosion rate. Especially keeping the target of the Green Deal and the Mission Board on Soil Health and Food in mind (Veerman et al., 2020) that aim to have 75% of all soil to be managed sustainably. For this the drip-irrigated, chemical farming practices on slopes in the Mediterranean should be taken under the loupe and the more sustainable terraces (dryland and flood irrigated) agriculture should be protected and promoted. This is a key issue to be researched to achieve a proper knowledge of the soil erosion processes (García-Ruiz et al., 2017).

Our research at the Peiró Camaró experimental farm contribute with a clear message of a non-sustainable management. This view is found also by other authors with measurements of the soil aggregate characteristics and their stability (Zheng et al., 2021), the impact on soil biota (Wu et al., 2021), and urgent need to use groundcovers to reduce the extreme soil erosion rates (Duan et al., 2020) and soil pollution (Zhang et al., 2020).

5. Conclusions

Thirteen-years soil erosion rates were measured in a representative modern drip-irrigation farm in Valencia region, the largest table oranges-clementines-tangerines-mandarines production area of the world. The results show a quick compaction of the soil in 13 years (from 1.05 till 1.33 g cm^{-3}), and high erosion rates that reached an average of 180 Mg ha^{-1} y^{-1}. Bulk density increased from 1.05 g cm^{-3} till 1.33 g cm^{-3} in 13 years. The extreme soil erosion rates measured in new drip-irrigated citrus plantations are the result of soil lowering in the centre of the inter-row and in the lower inter-row position due to extreme soil erosion rates that resulted in 80 cm of soil lowering in 13 years. In addition, the whole field underwent a lowering of the soil topography with no sedimentation processes within the plantation, which means that all eroded sediment was exported out of the field, causing damages elsewhere to infrastructures such as roads, drainage systems and wetlands. The data collected in 2007 and 2020 allow to distinguish between the impact of soil removal and soil compaction on topographical soil lowering. Soil erosion contributed with 91.5% and soil compaction with 8.5% of the total soil lowering in 13 years. The results of this study clearly show the urgent need for soil erosion control strategies to avoid soil degradation, loss of crop production and damages to infrastructures.

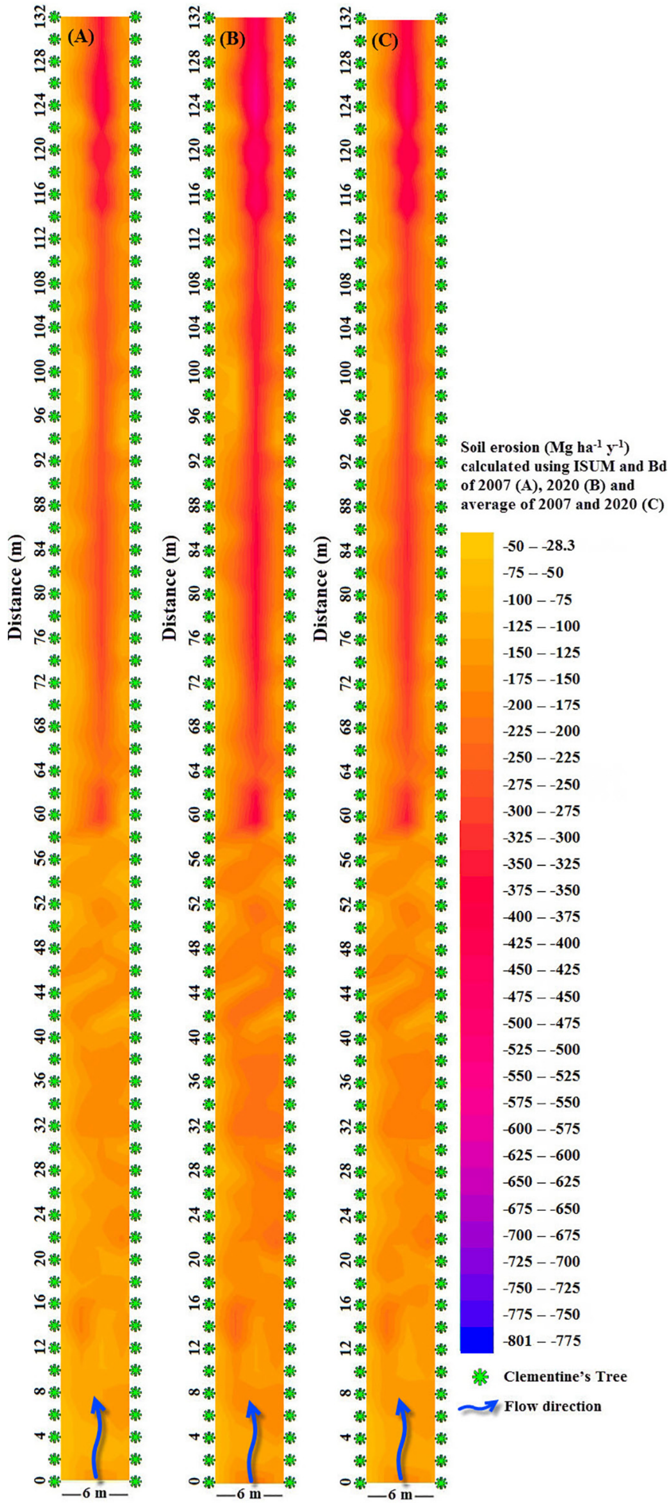

Fig. 4. Soil erosion rate obtained using ISUM and bulk density measured in 2007 and 2020, and the average between 2007 and 2020.

CRediT authorship contribution statement

Artemi Cerdà, Funding, data collection, data curation, data analysis, figure, writing.

Agata Novara, data data curation, data analysis, figures, writing.

Ehsan Moradi, data collection, data data curation, data analysis, statistics, writing.

Fig. 5. The impact of tractor passage on the soil compaction in the centre of the inter-rows at the Peiró-Camaró study site.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.147549.

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