# Landscaping compromises for land degradation neutrality: The case of soil erosion in a Mediterranean agricultural landscape

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Long title: Landscaping compromises for land degradation neutrality: the case of soil erosion in a Mediterranean agricultural landscape

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Abstract

Soil erosion is the primary process driving land degradation. Using multiple scales of management to minimize soil erosion is crucial to achieve land degradation neutrality targets within the Sustainable Development Goals agenda. Land management (LM) influences both on-site and off-site erosion on the event-scale and over the long-term. However, each LM differs in effectiveness depending on the temporal scale considered. In order to understand how LM effects internal and external catchment dynamics, we apply LandSoil, a physically based landscape evolution model, to evaluate 7 LM scenarios over long- (30 years) and short-terms (event scale). LM scenarios included changes in land use and/or landscape structure. Under current LM, mean surface soil erosion was ~ 0.69 ± $39 \cdot 10^{-3}$ m over 30 years. In contrast, a single extreme event (435 mm/24h) in January resulted in ~ 0.62 ± $3 \cdot 10^{-3}$ m loss and ~ 0.04 ± $2 \cdot 10^{-3}$ m if it occurred in October. Heterogeneous patterns of erosion and deposition developed after 30 years, whereas extreme events dominantly showed soil loss and high catchment connectivity. Effectiveness of LM in erosion mitigation and sediment trapping differed according to temporal and spatial scales for each scenario. We concluded that multiple temporal and spatial scales must be incorporated in order to adaptively manage land degradation and meet neutrality targets.

Key words:

Land degradation, Degradation neutrality, Soil erosion, Landscaping, Mitigation strategy

## 1. Introduction

Land degradation neutrality targets of the Sustainable Development Goals (SDG 15.3) contain time-specific measures to avoid, reduce and reverse land degradation at both national and subnational levels (The Global Mechanism of UNCCD, 2016). Soil erosion by water is a major land degradation process (Orr et al, 2017). Therefore, land management seeking to minimize soil erosion is crucial for maintaining food and water security, climate regulation, soil ecosystem services (Dominati et al., 2010; Koch et al., 2013; Lal, 2004; McBratney et al., 2014;

Montanarella et al., 2016; and achieving of multiple SDGs (Keesstra et al., 2016; Orr et al., 2017).

It is expected, that soil erosion and suspended sediment yield in rivers will increase beginning in the mid-21st century due to climate change (Raclot et al., 2018; Routschek et al., 2014a, 2014b, Bussi et al., 2016; Rodríguez-Blanco et al., 2016). The majority of soil loss occurs during high-magnitude events of low frequency/recurrence, especially in Mediterranean environments where 3-10 of the largest daily events can account for over 50% of total soil loss (González-Hidalogo et al., 2007, 2010). Due to climate change, the frequency of high-magnitude rainfall events increases (e.g., Serpa et al., 2015). Therefore, considering seasonal patterns of soil loss (Smetanová et al., 2018) alongside water and sediment connectivity, and evaluating economic effects of on- and off-site effects of land management are all essential for preventing land degradation (García-Ruiz et al, 2017; Raclot et al., 2018).

Land use influences both soil erosion (sediment production) and sediment connectivity, while landscape structure can influence sediment transport and connectivity (Ciampalini et al., 2012; Coulthard & Van De Wiel, 2017; David et al, 2014; Follain et al., 2006; Fryirs, 2013). Modelling studies shown, that proper management can reduce the future effects of climate change on mid- and long-term soil erosion rates (Parroissien et al.2015; Rodriguez-Lloveras et al., 2016; Routschek et al., 2014a, 2014b). Modelling approaches successfully tested the effects of crop allocation, sediment trapping, and ditch optimisation techniques under mean or extreme rainfall events (David et al, 2014; Furlan et al., 2012; Gumiere et al., 2014; Levavasseur et al, 2016; Mullan et al., 2016; Nunes et al., 2013; Ronfort et al., 2011).

However, in order to meet land degradation neutrality targets, it is crucial to focus land management simultaneously on the relevant spatial and temporal scales for erosional processes (Larson et al., 1997; Stroosnijder, 2005) and stakeholders' scales of practice (Smetanová, et al, 2018). This requires providing of multi-foci, multi-scale solution. For example, a management reducing sheet and gully erosion during high-magnitude events of low frequency/recurrence, and in long-term. Simultaneously, an effective management should reflect differing priorities of stakeholders operating in the same region. For example, the spatial scale of interests and mind-sets of a vineyards farmer and watershed manager might likely differ between understanding internal catchment dynamics on individual field scales (farmer) versus external catchment dynamics (e.g., sediment export to reservoirs). Furthermore, farmers establishing vineyards are interested in soil productivity over timescales that plants achieve highest productivity (10-30 years), while watershed managers might focus on reducing or preventing flash floods (single events). Understanding how land management effects on soil erosion contrast on temporal and spatial scales can help define targets for land management decisions aimed at reducing land degradation.

The objective of this study is to compare the internal and external catchment soil erosion dynamics for different land management scenarios over short-term (event scale) and long-term (30 years) scales, in order to answer the question: "Should management strategies for land degradation be tailored for specific spatial and temporal scales to achieve land degradation neutral management?"

## 2. Materials and Methods

### 2.1 Study site

The Roujan catchment (0.91 km$^2$), located in south France (43°30′N, 3°19′E) has been monitored for rainfall in the three meteorological stations equipped with tipping bucket rain gauges, and for continuous runoff and sediment concentration at parcel, mid- and whole catchment since 1992. It was described comprehensively by David et al. (2014). It belongs to a sub-humid Mediterranean climate (Peel et al., 2017) with mean annual rainfall 634 mm and a dry summer period, with maximum runoff and sediment yield from October to February. Elevation ranges 50m and slopes are 2–20% (David et al., 2014). Miocene marine and lacustrine sedimentary rocks with calcaric Regosols and Calcisols cover most of the catchment. Land use is dominated by vineyards (62%) followed by cereal and alfalfa production, and scrubland (Guix-Hébrard et al., 2007). Chemical weeding in vineyards is performed using herbicide application alongside mechanical weeding by shallow (0.05–0.10 m) tillage with a duck foot cultivator in spring and autumn (Biarnès and Colin, 2006; Coulouma et al., 2006). Wheat and barley are rotated in the fields with annual crops. Fields are treated biannually in the post-harvest period (summer–autumn) with a disc-and-chisel plough down to depths of 7 to 12 cm. Landscape structure is characterised by 140 fields (0.6 ± 0.5 ha) with grass, bare soil or vegetated compacted soil strips along field borders, and an 11-km network of ditches (David et al. 2014). Current land use and landscape structures represent baseline land use scenario (Figure 1).

## 2.3. LandSoil model

LandSoil model was previously developed and calibrated in Roujan catchment (Ciampalini et al. 2012), and since then applied in variety of environments (e.g., Ciampalini et al.2011; Chartin et al, 2011; Lacoste et al., 2016). LandSoil is a spatial raster-based model for simulating water and tillage soil erosion as well as evolution of topography at plot to catchment scale. After modelling each event, LandSoil recalculates the elevation raster. Soil surface properties control water infiltration, runoff, and sediment concentration for each grid-cell and rainfall event (David et al., 2014; Leonard and Andrieux, 1998). Runoff in each grid cell is combination of input from upstream/upslope cells and runoff generated within the cell. Runoff flows in the flow line direction, or, if flow lines are interrupted, along liner landscape elements (roads, ditches, field boundaries, and tillage rows). The model uses a modified single-flow runoff model (Jenson and Domingue, 1988; Souchère et al., 1998) under eight possible flow directions. Both contour and downslope tillage were modelled in different fields with tillage transport coefficients spanning 111–139 kg $m^{-1}$ (David et al., 2014).

## 2.4. Numerical experiment scheme

We considered two temporal dynamics (Figure 2):

(i) Long-term - 30 years. This period refers to long-term erosion rates over the timescale that a new vineyard will reach peak productivity.

(ii) Single extreme rainfall event – maximum measured daily rainfall event. Events were modelled for January and October in order to consider variability in soil surface properties (David et al., 2014) that arise during periods when large erosion events usually occur (Smetanová et al., 2018).

We considered two spatial dynamics:

(i) Internal catchment dynamics – represented by fine spatial resolution modelling (1-meter grid) to simulate erosion and deposition patterns over the entire catchment. It related to spatial scale of farmers.

(ii) External catchment dynamics – represented by sediment export at the catchment outlet. It related to sediment input to river system, and management scale of watershed managers and policy makers.

We applied seven predictive land use scenarios that combine narrative and modelling methods developed by David et al. (2014). Three narratives were (i) stationary production (B - "baseline", corresponding to current land mangement), (ii) more intensive production (I - "intensified"), and (iii) less intensive production (E - "extensified") than stationary production. These narratives were transformed into seven scenarios (BLUS, ILU; ILS; ILUS; ELU, ELS, ELUS) by modifying the baseline land use and / or landscape structure by allocation rules for of land use (LU) and landscape structure (LS) as described in Figure 3.

## 2.5. Model inputs

***Elevation and soil surface topography***

LIDAR-based digital elevation model derived at 2-m resolution (David et al., 2014) represented initial input topography for all scenarios. Elevation was recalculated after every/each event by subtracting the depth of eroded soil or adding the height of deposited sediment in each raster cell. Soil erosion rates and sediment export (in $Mg{\cdot}km^{-2}$, where 1 $Mg{\cdot}km^{-2}$ corresponds to 0.01 tonnes per hectare) at the catchment outlet were recalculated at the end of each simulation period based on equations provided by David et al. (2014).

***Rainfall dataset***

Long-term rainfall series were based on 10-years extension of empirical rainfall event measurements in the Roujan catchment between 1992-2012 (David et al., 2014; Figure 4). The total rainfall depth (mm), maximum intensity over 6 min (mm h–1) and rainfall duration (h) were considered for each event, separated by at least a 6-hour dry period.

An event with return period >100 years was represented by extreme event measured in Perpignan (120km from Roujan) on 26 October, 1915 (Cosadney and Robison, 2000; Meteo France, 2018). Rainfall depth was 435 mm over 24 hours, but no measurement of rainfall intensity was available. Rainfall intensity was estimated using the Montana law, with results suggest that the Montana coefficient value exceeded the maximum intensity class for the LandSoil model. Therefore, the maximum rainfall intensity class (>40 mm $h^{-1}$) was applied based on calibration from Ciampalini et al. (2012). Model parameters and soil conditions are described in additional detail by David et al. (2014).

***Tillage Dataset***

Modelled tillage events occurred in fields with annual crops and in vineyards with mechanical weeding. We simulated tillage twice a year in April or May and October. The exact day of a tillage simulation was determined by cumulative rainfall depth (40 mm) since the last tillage event.

3. Results

3.1 Temporal dynamics: Long-term vs. extreme event soil erosion

Under current land use and landscape structure conditions (BLUS), mean soil loss was 0.69 ± $38.97 \cdot 10^{-3}$ m across the catchment over the 30-year simulation period (Table 1). Mean soil loss here is the mean of all raster-cell values after 30 years of simulation. Each raster-cell value represented cumulative elevation change after 30 years of simulation. Soil export at the outlet (i.e., external catchment dynamics) under BLUS scenario was $9.02 \cdot 10^{-2}$ $Mg \cdot km^{-2}$. Soil export at catchment outlet varied from 4.74 (ELUS) to 119.20·$10^{-2}$ Mg·$km^{-2}$ (ILUS).

Erosional responses to single extreme rainfall events differed from long-term (30 years) cumulative soil loss and were different for January and October. Mean soil loss in single extreme rainfall event was 0.60 ± 2.72·$10^{-3}$ m in January, and 0.00 ± 1.55·$10^{-3}$ m in October under BLUS scenario. Sediment export (external dynamics) was 16.4x higher in January than in October. Similar patterns were observed in other scenarios, where mean soil loss for extreme events were 1.3x (ILU) to 20x (ELS) higher in January relative to October.

Comparing mean soil loss of long-term and extreme events (Table 1) under BLUS scenario showed that 8.3±14-times more soil was eroded after thirty years than by a single extreme event in January.

Sediment exported by a single event in January or October is only reached as the cumulative effect of many erosion events under normal rainfall conditions. This comparison could be called 'equal erosion delivery', which refers to the duration required for continuous "normal" erosion to match the quantity of sediment delivered by an extreme event. In BLUS, sediment exported in January was reached after ~27 years, while sediment exported during October was matched after ~2 years. Sediment exported in all January extreme events was reached in ~21-26 years under extensified land use scenarios, but dropped drastically to~2-4 years if October extreme events were considered. Under ILU and ILUS, soil loss by both extreme events were more similar than by all remaining scenarios. Under long-term rainfall conditions, an equivalent amount of sediment export was reached in 6-7 years.

## 3.2 Internal catchment dynamics

Long-term rainfall conditions under current land use and landscape structure (BLUS) led to soil redistribution within the catchment (Figure 5B). Soil loss ranged from 0.01 to 0.3 m in vineyards with chemical weeding, with less than 0.01 m loss in scrubland and no tillage annual crop fields. In vineyards with mechanical weeding and in fields with tilled annual crops, erosion ranged from 0.01 to 0.3 m and deposition >0.01 m occurred. Rills created in parcels with no tillage and scrubland were infilled by shallow deposition (<0.01 m). Zero net erosion or deposition (<$10^{-12}$m) was observed on or along linear landscape structures (e.g., roads, field borders).

In contrast to previous results, during an extreme event in January (Figure 5C), net soil loss was 0.01 to 0.3 m in all land uses excluding scrubland, where a series of long rills with depths < 0.01 m, were created. Rills deeper than 0.3 m were formed along some recent and/or historical linear landscape structures. Deposition > 0.1 m only took place on some of the vegetated strips. During an extreme event in October, mean soil loss was lower than that from extreme events in January (Table 1). Furthermore, the rill network within scrubland and along field borders was less dense and generally, shorter rills infilled with less than 0.01 m sediment (Figure 5D). “Equal erosion delivery” duration was ~27-years for an extreme event in January. However, soil redistribution patterns were completely different (Figure 5E). Sediment exported during an extreme rainfall event in October was reached after ~2 years of long-term rainfall conditions (Figure 5F), but contrary to extreme rainfall in October (Figure 5D) nearly zero erosion or deposition occurred within most of the parcels under normal rainfall conditions.

For other scenarios, the relation between long-term and extreme event internal catchment dynamics was similar to those in BLUS (Supplementary Info 1). Normal rainfall simulations led to heterogeneous soil redistribution patterns with areas of both erosion and deposition after 30 years, while nearly zero net soil erosion over the majority of the catchment during extreme events.

Differences in internal catchment dynamics for each temporal scale are shown using an example of upper (terraced) slopes divided to two parcels (Figure 6). The upper parcel was divided to one (ILS) or more (BLUS, ELS) fields with mechanical weeding. Chemical weeding was applied in ILU and ILUS scenarios, while scrubland covered the parcel in ELU and ELUS (Figure 6A). The lower parcel was covered by scrubland in all scenarios, but the field border cover varied (Figure 6A). Under scenarios of intensified land use (ILU and ILUS), 0.01-0.3 m of soil was removed from surface in vineyards with mechanical weeding. Furthermore, deep rills (0.01-0.3 m) in scrublands were infilled with transported material after 30 years (Figure 6B). During extreme events in January (Figure 6C), the scrubland rill network was much less dense compared to long-term simulations. However, during extreme event in January some of the partly infilled rills cut into adjacent field borders and continued eroding. Additionally, exclusively soil erosion occurred downhill of the scrubland field border during extreme events in January. Substituting vegetated pathways with bare soil (Figure 6A-ILS) increased connectivity between parcels and concentration of overland flow from upper parcel in lower parcels under long-term rainfall conditions (Figure 6B-ILS). During extreme events (Figure 6C, 6D –ILS) erosion <0.01 m occurred along some rills in scrubland. Under ILS, equal erosion delivery was attained after 17 years in comparison to January extreme event. Soil redistribution after 17 and 30-years under ILS was similar. For ILU and ILUS, equal erosion delivery was 7 and 6 years. Again the soil erosion pattern of equal soil erosion delivery was similar to long-term soil redistribution pattern (Figure 6E –ILU and ILUS).

Under ELU overland flow generated in upper parcel (scrubland, Figure 6A-ELU) caused less intensive erosion on-site than vineyards parcels in stationary and more intensive production scenarios in 30 years (Figure 6B). Furthermore, scrubland led to rill formation and their infilling in lower parcel after 30 years (Figure 6B-ELU). In ELUS, combined land use and landscape structure changes helped protect rill incision (Figure 6B ELUS), but as Figure 6B ELS shows, change of landscape structure alone was not sufficient to prevent rill erosion. Under extreme events, erosion was low along scrubland field borders, and downslope rills emerged only under ELS. During the year when sediment export from long-term rainfall conditions equalled extreme events, soil redistribution patterns was more related to long-term precipitation patterns (Figure 6, Supplementary Info 1).

### 3.3 External catchment dynamics

Sediment export is referred to external catchment dynamics, and is reported in section 3.1, Table 1. In scenarios with intensified land use (ILU, ILUS), total sediment export over long-term conditions was over 10-fold higher than BLUS, over 4-fold higher than ILS. Total sediment export under extreme event in January was in ILU and ILUS over 2.6-fold higher than BLUS, and over 1.6-fold higher than ILS. For scenarios with less intensive production than BLUS, long-term sediment export at catchment outlet by 10% (ELU), 40% (ELS) and 50% (ELUS) in comparison with BLUS sediment export.

Sediment export under all scenarios was increasingly stable over the first four years of model simulations, followed by sudden increases in the fifth year triggered by rainfall (Figure 7). The sediment export response to natural rainfall conditions differed between the modelled scenarios. Intensified scenarios responded with higher sediment production (i.e., erosion) and transport. Soil export in ILUS more than doubled, and increased ~1.5-fold in ILU and ILS (Figure 7B). On the contrary, ELU exhibited increased sediment export than ELS. Threshold behaviours with different magnitudes of sediment response existed for all scenarios in several years (e.g., year 16, year 24).

Figure 7B compares sediment export by extreme events in January with long-term sediment export. Intensified scenarios reached the sediment export of BLUS within first 4 to 10 years (for ILUS and ILS, respectively).

## 4. Discussion

### 4.1 Land management optimisation: understanding the impact on differing temporal scales

Comparing scenarios over different time scales showed that both external and internal catchment dynamics differed for long-term and extreme-event rainfall conditions. Mean and variability of soil loss were greater after long-term rainfall events than extreme rainfall conditions. However, sediment export at the catchment outlet from a single extreme event (in January) accounted for 89% (BLUS) of long-term sediment export. Within-catchment and within-parcels erosional hotspots formed over the 30 year simulations. Hotspots' spatial distribution differed for each land use scenario, while landscape structure influenced within-catchment (dis-) connectivity. Soil redistribution within parcels was strongly influenced by erosion from tillage (David et al, 2014), which temporarily influences soil properties and micro-landforms (e.g., infilling rills, creating tillage rows) and thus, hydrology and associated sediment connectivity along hillslopes.

During extreme events, most of the catchment was connected. Soil erosion removed up to 0.01-m from almost the entire catchment independent of land use or landscape structure (except for scrubland and some of the filed borders, grass strips, pathways). Land uses or landscape structures sometimes acted as barriers or buffers under normal rainfall conditions, but were less effective in damping overland flow and sediment trapping. Yet, effects of single extreme rainfall events differed for October and January depending on soil-vegetation properties in the respective month. In October, transport-limited deposition took place in some pathways, whereas only transport and zero net erosion or deposition took place in January. Antecedent conditions such as previous rainfall or tillage influenced sensitivity of sediment response to seasonal changes in soil hydrological properties, demonstrated previously by monitoring studies (e.g., Biddocu et al., 2017; Inoubli et al., 2017; Raclot et al., 2009, Smetanova et al., under revision).

## 4.2 Land management optimisation: understanding effects of management measures under different scenarios

We discuss the effect of land management on land-degradation based on area-specific sediment budgets for both long-term and extreme events (Figure 8).

Chemical weeding led to erosion when applied on vineyards in all scenarios and timescales. Mechanical weeding, was also a net source of sediment under extreme rainfall conditions in January, but over 30 years, had nearly neutral sediment budget. According to David et al. (2014), mechanical weeding caused three-times less sediment erosion compared to chemical weeding over 100 years. However, extensive mechanical weeding in ELU without using extensive landscape structures (such as in ELS) increased sediment export more than both current land use and extensive landscape structure in ELS (Table 1). This confirms that land use and landscape structure management must be used in combination to effectively decrease both sediment production (i.e., erosion) from farmers' fields and sediment exported from the catchment to river system.

Grass strips and vegetated strips were the most effective management strategies for trapping

sediment at both temporal scales (and in 100 years as in David et al., 2014), but the sediment trapped was highest for extreme events. Total area and spatial distribution of vegetated strips was identical under BLUS; ILU and ILUS, but sediment trapping in vegetated strips decreased with decreasing sediment production. Sediment trapping efficiency of vegetated strips differed with (i) amount of sediment produced, (ii) spatial redistribution of landscape elements and land uses, and (iii) single (process) versus cumulative events (long-term processes). Trapping efficiency was directly linked to sediment connectivity during extreme events and over the long-term. This confirm previous findings that both sediment connectivity and sediment trapping efficiency are dependent on spatial distribution of management (Collin et al., 2012; Gumiere et al., 2011; Mekonnen et al., 2015; Ramos et al., 2010). Using a raster-based approach allowed us to assess sediment production and transport at individual parcel scale at both temporal scales (example in Figure 6). However, we did not calculate soil loss and effectiveness of measures for each farmer at different time scales, which is possible and recommended for supporting decision-making schemes (Souchère et al., 2010). At the catchment scale, soil surface properties drove sediment export regardless of land use (David et al., 2014). Therefore, management techniques aimed at the soil surface can reduce soil erosion. Such approaches include straw mulch or intercropping, and are known to decrease soil erosion under long-term and extreme rainfall conditions (Biddocu et al., 2014, 2016, 2017; Blavet et al., 2009; Cerdà et al., 2016; Gómez et al., 2009, 2014; Kosmas et al., 1997; Prosdocimi et al., 2016; Raclot et al., 2009; Ramos et al., 2007; Rodrigo-Comino et al., 2016; Ruiz-Colmenro et al., 2011).
Management strategies can be either (i) permanently incorporated in land use scenarios, or (ii) used in conjunction with others (e.g., geotextiles, mobile sediment trapping barriers) as ad-hoc measures during extreme events (Sherrif et al., 2016).

### 4.3 Pathways for applicable optimisation for land-degradation neutral management

Our results suggest that using multiple temporal, spatial and management scales to evaluate soil erosion and connectivity can significantly improve existing modelling approaches (Bussi et al., 2016; Collin et al., 2012; David et al., 2014; Gumiere et al., 2014; Mullan et al., 2016; Nunes et al., 2013; Paroissien et al, 2015; Ramos et al., 2015; Rodriguez-Lloveras et al., 2016; Ronfort et al., 2011; Routschek et al., 2014). Our approach includes temporally- and spatially-adjusted measures that are applicable for meeting soil erosion and land degradation neutrality targets (The Global Mechanism of UNCCD, 2016). We demonstrate that proposing land degradation neutrality measures in agricultural catchments is extremely complex due to (i) natural variability of catchment responses to normal rainfall conditions and extreme events, and (ii) variability in cumulative response depending on the spatial distribution of selected measures. Furthermore, we showed that (iii) the same sediment export (sediment yield) values represented different patterns of soil erosion and deposition within a catchment. The complexity of applying measures to reduce land degradation is reinforced by differing interests and management aims of each stakeholder (e.g., farmer or watershed manager; Smetanová et al., 2018). Therefore, modelling approaches applied on differing spatial and temporal scales are valuable aid for participative decision making on best practice management (Hewett et al., 2018, Keesstra et al., 2018).

## 5. Conclusion

Our research proved, that tailoring specific management strategies for specific spatial and temporal scales might be suitable in order to achieve land degradation neutral management. Our research contributions included the following in regards to attaining land degradation neutrality goals:

1. Managing changes to land use or cover won't appropriately serve land degradation neutrality targets at the catchment scale (sub-national level). It is essential to include landscape structure change and connectivity management into land use scenarios.
2. Internal and external catchment dynamics differ for long-term and extreme events, and therefore multiple temporal, spatial, and management scales must be compared and incorporated in to planning adaptive management for land degradation. Optimally, this will span from farm- to catchment-scales, as well as sub-national levels.
3. Modelling approaches such as LandSoil enable comparison of management efficiency for both long- and extreme event-scales. Additionally, the model improves selection of

timely and adaptive management scenarios best serving land degradation neutrality targets (SDGs 15.3)

We suggest that holistic land degradation neutrality management can be selected by using multi-scale consideration based on models incorporated in participative decision making. Using such inputs will bring multiple co-benefits fostering life on land, including avoiding, reducing and reversing land degradation processes.

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Figure description:

Figure 1. Study area (A), land use (B), and landscape structures (C)

Figure 2: Flowchart of numerical experiment in LandSoil. Model inputs were digital elevation model, dynamic soil properties, seven land management scenarios, and rainfall. Two temporal (long-term, single event) and two spatial dynamics (internal and external) were considered. Red triangle indicates management priorities of a farmer, inverted red triangle priorities of a watershed manager. Outputs related to internal (v) and external (inverted v) catchment dynamics were produced for each scenario.

Figure 3. Land management allocation matrix.

Figure 4. The full 30 years of precipitation data plotted over time. First 20 years (red frame) are empirically measured rainfall events in Roujan (1992-2012), while the last 10 years are extension of the empirical dataset. The red star represents the amount of rainfall during the extreme event (435 mm/24h) measured in Perpignan in 1915.

Figure 5. Internal catchment dynamics under current land use and landscape structure (BLUS)
A: Land use and landscape structure, B-F: Erosion and deposition: (B) after 30 years of normal rainfall conditions, (C) after an extreme event in January, (D) after an extreme event in October. (E) internal catchment dynamics in year (indicated by number) when sediment export by the long-term rainfall series matches that of an extreme event in January, and (F) same as E, but for an extreme event in October. An elevation change legend (bottom right) shows deposition as positive, erosion as negative, and anything $<10^{-12}$m and $> -10^{-12}$m as "no erosion, no deposition".

Figure 6. Internal catchment dynamics in one selected catchment segment
Land use and landscape structure(A), and erosion and deposition on different time scales (B-F) under different scenarios (indicated by rows) are shown in the selected catchment segment (locator figure, left bottom). Time scales: (B) 30 years under normal rainfall conditions, (C) an extreme event in January, and (D) an extreme event in October. In columns E and F, internal catchment dynamics are shown for the year when catchment outlet sediment export under long-term rainfall series met that of

an extreme event (E) in January and (F) in October.

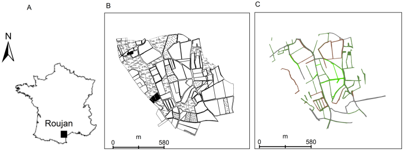
Baseline scenario (B) represents steady production under current land use (LU) and landscape structure (S). More intensive (I) production than steady production is represented by ILU, ILS, ILUS scenario, less intensive (E) production by ELU, ELS, ELUS.

An elevation change legend (bottom right) shows deposition as positive, erosion as negative, and anything $<10^{-12}$m and $> -10^{-12}$m) as “no erosion, no deposition”.

Figure 7. External catchment dynamics

(A) Area specific sediment yield at the catchment outlet ($10^{-2}$ Mg·km$^{-2}$) over 30 years. (B) Comparison between sediment delivery over long-term (30 years) and extreme events in January (arrow). Baseline scenario (B) represents steady production under current land use (LU) and landscape structure (S). More intensive (I) production than steady production is represented by ILU, ILS, ILUS scenario, less intensive € production by ELU, ELS, ELUS.

Figure 8. Land management effect on land degradation under different scenarios and temporal scales. Area-specific sediment budget within landscape management ($10^{-2}$ Mg·km$^{-2}$) is plotted for long-term (30 years, x-axis), and an extreme event in January (y-axis). Erosion is plotted in red and orange, deposition in green and blue.

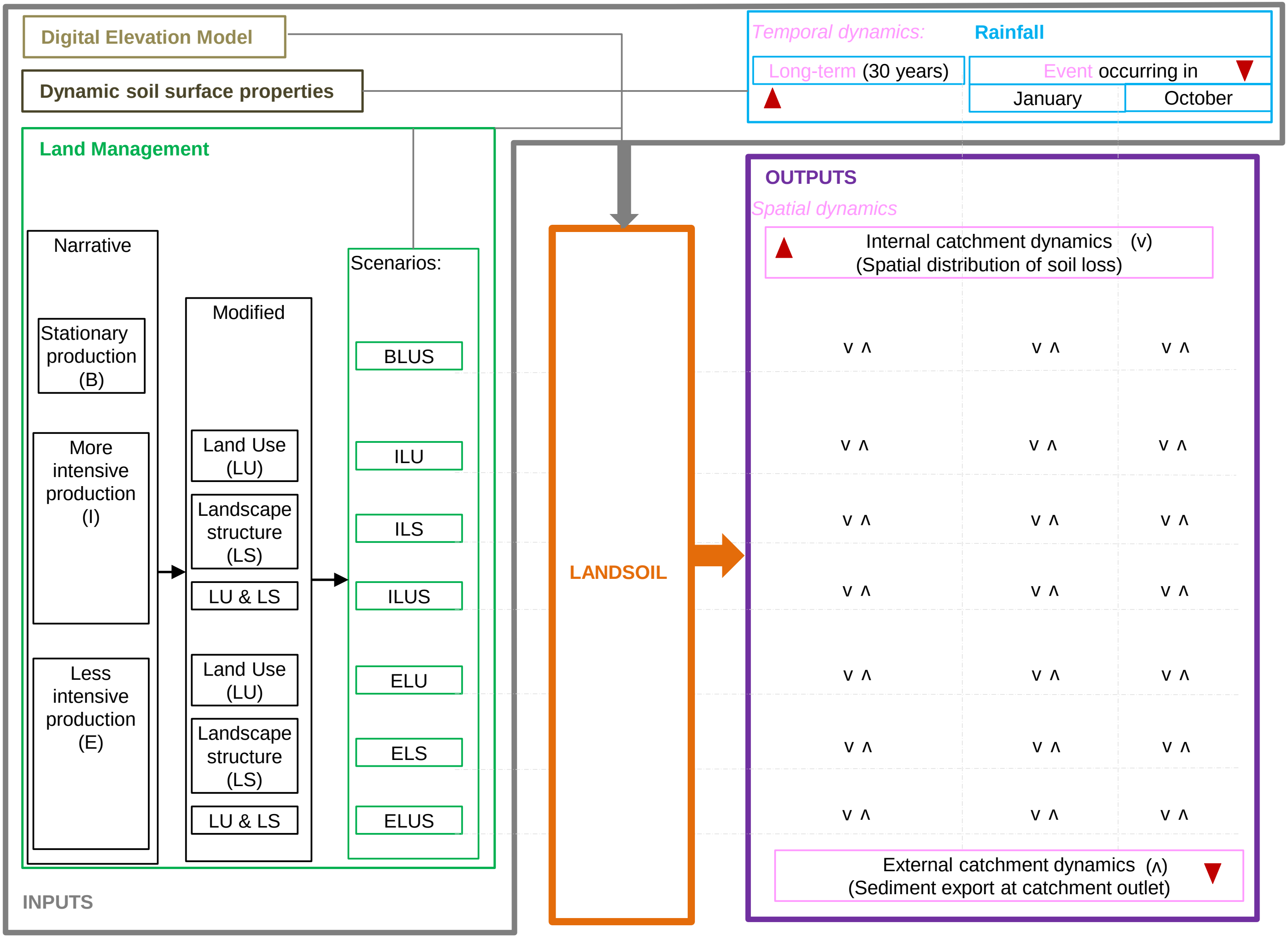



Baseline scenario: (A) land use and (B) landscape structure

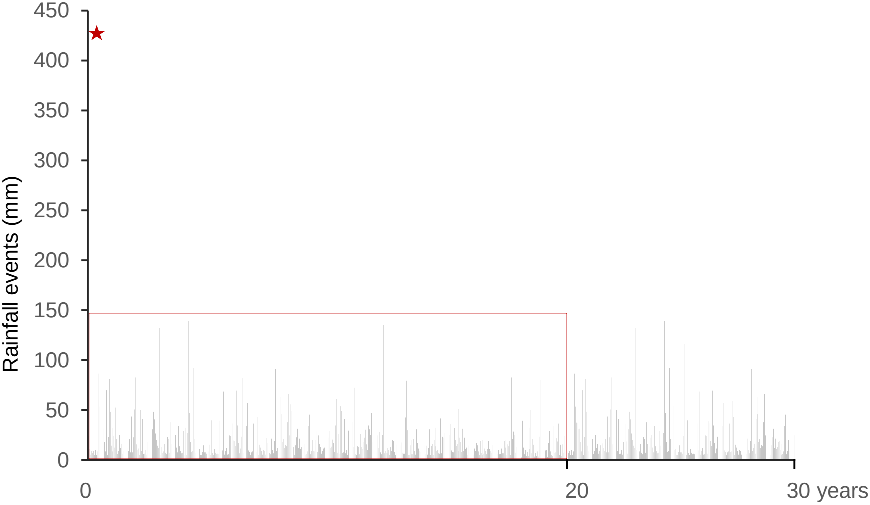
- vineyards - mechanical weeding
- vineyards - chemical weeding
- annual crops - tillage
- fruit trees
- scrubland
- annual crops - no tillage
- pathway - bare soil
- pathway - vegetated soil
- grass strip
- building
- paved road

| Management | | Narrative | | |
|---|---|---|---|---|
| | | Stationary production (B) | More intensive production (I) | Less intensive production (E) |
| Landuse (LU) | Area: vineyards and crop | - | ↑ | ↓ |
| | Area: chemical weeding | - | ↑ | ↓ |
| | Area: no tillage | - | ↓ | ↑ |
| Landscape structure (LS) | Field unit surface | - | ↑ | ↓ |
| | Linear structure density | - | ↓ | ↑ |
| | Downslope tillage direction | - | ↑ | ↑ |
| | Area: grass strips | - | ↓ | ↑ |

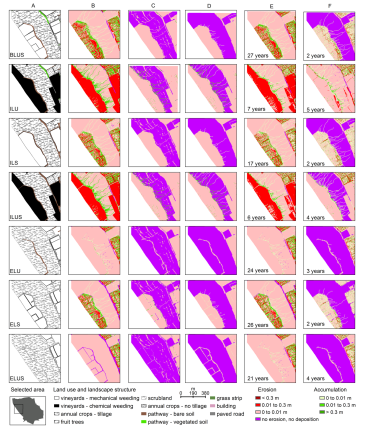
Scenarios were build according to three narratives: (B) – stationary production (representing current conditions), (I) more intensive production and (E) less intensive production than current conditions. Land use (LU) and/or landscape structure (LS) management was modified by increase (↑) or decrease (↓) in total area, and change in spatial allocation of LU and/or LD management in comparison with stationary production (-). The abbreviations of resulting seven scenarios (BLUS, ILU, ILS, ILUS, ELU, ELS, ELUS) indicate the narrative (B, I, S) and management (LU, LS, or LUS- both LU and LS). Detailed rules on allocation are in David et al. (2014). Spatial allocation of BLUS is plotted in Figure 5A (BLUS), and remaining scenarios in Supplementary Info 1.1A-1.6A.



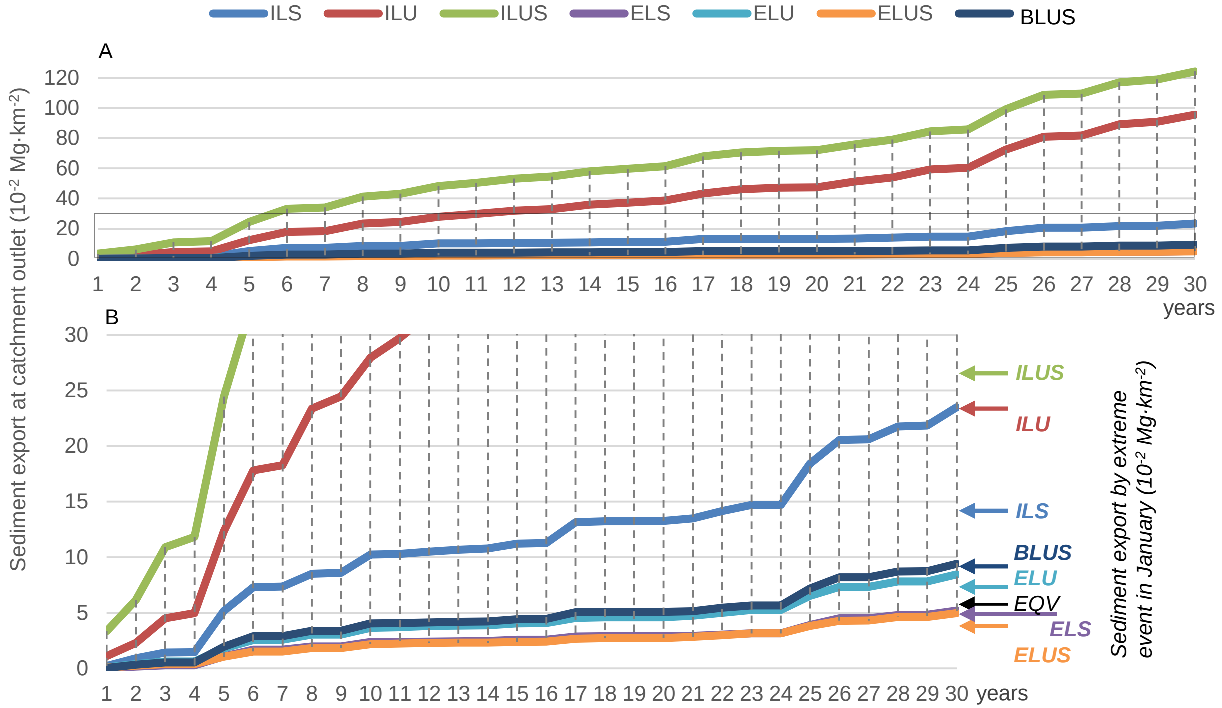
Digital Elevation Model
Dynamic soil surface properties
Temporal dynamics:
Rainfall
Long-term (30 years)
Event occurring in
January
October
Land Management
Narrative
Stationary production (B)
More intensive production (I)
Less intensive production (E)
Modified
Land Use (LU)
Landscape structure (LS)
LU & LS
Land Use (LU)
Landscape structure (LS)
LU & LS
Scenarios:
BLUS
ILU
ILS
ILUS
ELU
ELS
ELUS
LANDSOIL
OUTPUTS
Spatial dynamics
Internal catchment dynamics (v)
(Spatial distribution of soil loss)
External catchment dynamics (ʌ)
(Sediment export at catchment outlet)
INPUTS


Rainfall events (mm)
450
400
350
300
250
200
150
100
50
0
0
20
30 years

A
B
C
D
E
27 years
F
2 years
Land use and landscape structure
vineyards - mechanical weeding
vineyards - chemical weeding
annual crops - tillage
fruit trees
scrubland
annual crops - no tillage
pathway - bare soil
pathway - vegetated soil
grass strip
building
paved roads
Erosion
< 0.3 m
0.01 to 0.3 m
0 to 0.01 m
no erosion, no deposition
Accumulation
0 to 0.01 m
0.01 to 0.3 m
> 0.3 m



A
B
C
D
E
F
BLUS
27 years
2 years
ILU
7 years
5 years
ILS
17 years
2 years
ILUS
6 years
4 years
ELU
24 years
3 years
ELS
26 years
2 years
ELUS
21 years
4 years
Selected area
Land use and landscape structure
vineyards - mechanical weeding
vineyards - chemical weeding
annual crops - tillage
fruit trees
scrubland
annual crops - no tillage
pathway - bare soil
pathway - vegetated soil
grass strip
building
paved road
m
0 190 380
Erosion
< 0.3 m
0.01 to 0.3 m
0 to 0.01 m
no erosion, no deposition
Accumulation
0 to 0.01 m
0.01 to 0.3 m
> 0.3 m


ILS
ILU
ILUS
ELS
ELU
ELUS
BLUS
A
B
Sediment export at catchment outlet (10-2 Mg·km-2)
years
ILUS
ILU
ILS
BLUS
ELU
EQV
ELS
ELUS
Sediment export by extreme event in January (10-2 Mg·km-2)

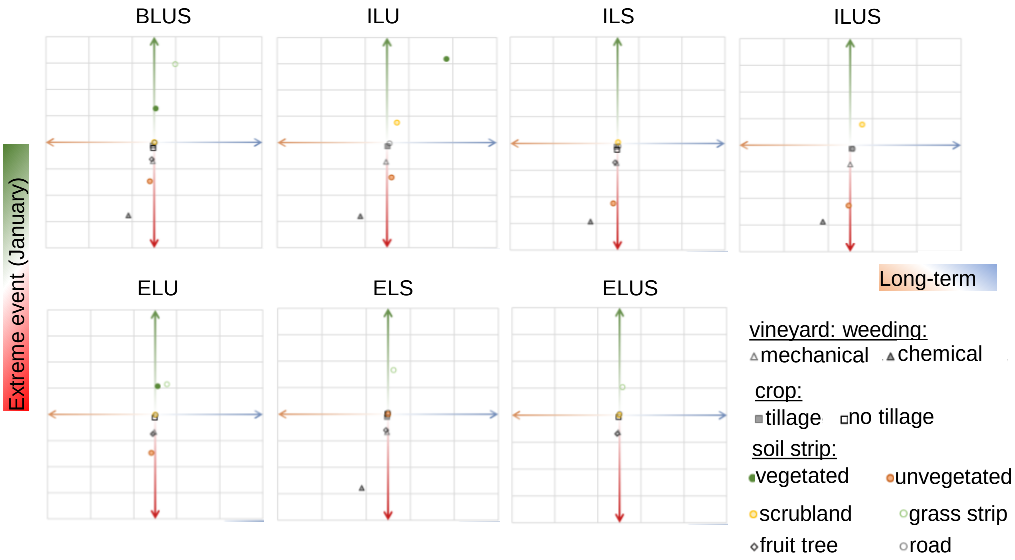

BLUS
ILU
ILS
ILUS
ELU
ELS
ELUS
Extreme event (January)
Long-term
vineyard: weeding:
mechanical
chemical
crop:
tillage
no tillage
soil strip:
vegetated
unvegetated
scrubland
grass strip
fruit tree
road

Table 1. Mean soil loss for the catchment and soil export at catchment outlet under each scenario

| | Long-term erosion | | | Extreme event in | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | January | | | | October | | | |
| | Mean soil loss* | Soil export at outlet | | Mean soil loss* | Soil export at outlet | | Equal ** | Mean soil loss* | Soil export at outlet | | Equal ** |
| | $10^{-3}$m | Mg | $10^{-2}$ Mg·km$^{-2}$ | $10^{-3}$m | Mg | $10^{-2}$ Mg·km$^{-2}$ | years | $10^{-3}$m | Mg | $10^{-2}$ Mg·km$^{-2}$ | years |
| BLUS | 0.69±38.97 | 856.11 | 9.02 | 0.62±2.71 | 762.10 | 8.03 | 26.7 | 0.04±1.55 | 46.16 | 0.49 | 1.6 |
| ILU | 7.05±80.47 | 8700.59 | 91.70 | 1.62±4.39 | 1996.81 | 21.05 | 6.9 | 1.18±4.38 | 1456.43 | 15.35 | 5.0 |
| ILS | 1.73±35.69 | 2135.83 | 22.51 | 0.99±2.16 | 1216.83 | 12.82 | 17.1 | 0.09±0.74 | 112.82 | 1.19 | 1.6 |
| ILUS | 9.17±52.68 | 11309.58 | 119.20 | 1.89±3.44 | 2334.57 | 24.60 | 6.2 | 1.17±3.26 | 1445.42 | 15.23 | 3.8 |
| ELU | 0.62±25.16 | 769.80 | 8.11 | 0.50±2.01 | 614.55 | 6.48 | 23.9 | 0.07±1.16 | 88.06 | 0.93 | 3.4 |
| ELS | 0.38±35.01 | 469.59 | 4.95 | 0.33±3.10 | 412.83 | 4.35 | 26.4 | 0.03±1.38 | 36.87 | 0.39 | 2.4 |
| ELUS | 0.36±19.43 | 449.81 | 4.74 | 0.26±2.47 | 318.81 | 3.36 | 21.3 | 0.05±1.35 | 57.60 | 0.61 | 3.8 |

*- mean calculated based on raster cells, ± indicates standard deviation. Mean soil loss is also referred to as internal catchment dynamics in the text. Soil export is also referred to as external catchment dynamics in the text. **- number of years in which catchment outlet sediment export over long-term rainfall matched that of extreme events; BLUS-steady production - baseline land use and landscape structure. I-more intensive production than B. E-less intensive production than B; $10^{-2}$ Mg·km$^{-2}$ equals t/ha