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TERRACED VINEYARDS OF THE DOURO WINE REGION, PORTUGAL: A SOIL AND WATER MANAGEMENT PERSPECTIVE

Viñedos en terrazas en la región vitivinícola del Duero, Portugal: una perspectiva de la gestión del suelo y el agua

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ABSTRACT: The Douro vineyards are a striking example of soil protection materialized in a strongly humanized landscape, where terraces cover a large part of the region. The paper aims at presenting a perspective on soil and water management improvements for Douro terraced vineyards, as a response to actual responsibilities determined by the UNESCO World Heritage statute in preserving a cultural, living and evolutional landscape. After stressing the importance of Douro terraced vineyards in the Portuguese Continental territory and the natural constraints for crop production characterizing the Douro valley, terrace types present in Douro landscapes are described, together with soil changes with terracing operations. Besides the rehabilitation of drystone structures as part of the preservation interventions on the region's cultural heritage, critical risk areas in recently terraced hillslopes are identified as a priority for soil protection and water management interventions. These are the vineyard areas most expose to direct impact of erosive rainfalls and comprise the inter-row lanes, especially in non-terraced vineyards, the earthen bare risers in recent terraces, and the farm road and drainage networks, spatially coincident, in steep extensively planted hillslopes. Innovative soil and water management practices have to be developed and locally tested in close dialog with regional actors.

KEY WORDS: Soil protection; drainage network; critical risk areas; terraced soil; terrace types; drystone walls.

RESUMEN: Los viñedos del Duero son un ejemplo sorprendente de protección del suelo, materializado, en un paisaje fuertemente humanizado, donde las terrazas cubren una gran parte de la región. Este trabajo tiene como objetivo presentar una perspectiva sobre las mejoras en la gestión del suelo y el agua en los viñedos en terrazas del Duero, como respuesta a las responsabilidades reales determinadas por el estatuto del Patrimonio Mundial de la UNESCO, para preservar un paisaje cultural, vivo y evolutivo. Después de enfatizar sobre la importancia de los viñedos en terrazas del Duero en el territorio continental portugués y las limitaciones naturales para la producción de cultivos que caracterizan el valle del Duero, se describen los tipos de terrazas presentes en el paisaje del Duero, junto con los cambios en el uso del suelo debido a las operaciones de las terrazas agrícolas. Además de la rehabilitación de las estructuras de piedra seca como parte de las intervenciones de preservación del patrimonio cultural de la región, las áreas de riesgo crítico en las laderas aterrazadas identificadas recientemente se identifican como una prioridad para las intervenciones de protección del suelo y gestión del agua. Se trata de las áreas de viñedos más expuestas al impacto directo de las lluvias erosivas y comprenden los pasillos entre líneas de la vid, especialmente en viñedos no aterrazados, los taludes desnudos de tierra en terrazas de origen reciente, y las redes de caminos y drenaje agrícolas, espacialmente coincidentes, en laderas empinadas plantadas extensivamente. Prácticas innovadoras de gestión del suelo y agua deben desarrollarse y probarse localmente en un diálogo cercano con los actores regionales.

PALABRAS CLAVE: Protección del suelo; red de drenaje; áreas de riesgo crítico; suelo en terrazas; tipos de terrazas; muros de piedra seca.

1. Introduction

The Portuguese territory comprises the mainland, west in the Iberian Peninsula facing the Atlantic Ocean, named Continental Portugal, and the Atlantic islands, grouped in the Azores and Madeira Archipelagos. The Portuguese continental territory is a land of contrasts, where the Tagus River splits apart the Northern hilly country from the lowlands of the Southern half. In fact, north of the Tagus, 75% of the territory is above 200 m elevation, with an average altitude of 370 m, while in the southern tract of the country the mean elevation is 160 m, with 62% of the area below 200 m (Medeiros, 1987; 2005). The most impressive mountain ranges are aligned from NW, near the coast, to SE, inland, the top of *Serra da Estrela*, north of the Tagus, in the Central Massif, reaching 1993 m. This general physiographic picture readily indicates a geomorphologically active natural setting, in which hill-slope processes as runoff erosion play an important role.

Terraced landscapes may be understood as an outcome of the human intelligent struggle for survival in rough terrain. Through time, highlanders realized that sustainable settlement in such difficult conditions could only be achieved caring for soil conservation and water management, to grow crops and ensure food and eventually revenue. Therefore, mountain and steep sloping farmland has to be associated since its origins to a refined knowledge of the natural setting and a wise use of so crucial resources as soil and water. Terraces are the most achieved result of such quest for better life in a harsh environment, no matter the large efforts required or the short benefits obtained. And this is also the case of the Portuguese terraced landscapes.

In present times, terraces are common elements of the Portuguese mountain and steep-sloping areas. Figure 1 depicts the cartography of terraces available for Continental Portugal, which assembles data issued from soil maps, hence not specifically driven to survey terraces (soil maps of: *Trás-os-Montes e Alto Douro*, NE, by Agroconsultores & Coba, 1991; *Entre Douro e Minho*, NW, by Agroconsultores & Geometral, 1995; *Beira Interior*, Centre East, by Geometral & Agroconsultores, 2005). Figure 1 also depicts vineyards distribution in Continental Portugal, based on the 2015 land use map (DGOT, 2019b), and outlines the overlapped data layers of terraced and vineyard areas, labelled as terraced vineyards. As expected, terraces are mostly present north of the Tagus River, where also lay three most representative Wine Regions of Portugal: Dão e Lafões, Douro and Vinhos Verdes. According to the sources of Figure 1, terraced areas cover 2.9% of Continental Portugal, while areas planted with vineyards correspond to about 2.1%, and terraced vineyards to 0.3%, meaning near 23 thousand hectares (Table 1). Vinhos Verdes Wine Region accounts for the larger area of terraces (in absolute and in relative terms) but, as also in the Centre-East of the country, they are not dominantly occupied by vineyards. The Douro Wine Region has the larger extent of terraced vineyards (5.7% of the Region, near 1/4 of the regional vineyards area), which represents almost 1/3 of terraced vineyards in Continental Portugal.

Part of the Douro Wine Region, the *Alto Douro Vinhateiro* (24,600 ha), was granted the UNESCO World Heritage status (2001), in recognition of the values it encloses as a living and evolutional cultural landscape (Bianchi-de-Aguiar, 2002). This distinction implies an increased responsibility for territorial actors and managers. Indeed, the Alto Douro Vinhateiro has to keep improving and innovating on solutions to achieve a difficult balance between opposing strains in different dimensions. They combine management with valuing (the meager resources and the excellence of the products), building with preservation (of the evolutional and living landscape, diverse and unique), prevention with mitigation (of risks and natural hazards that compromise resources and productions).

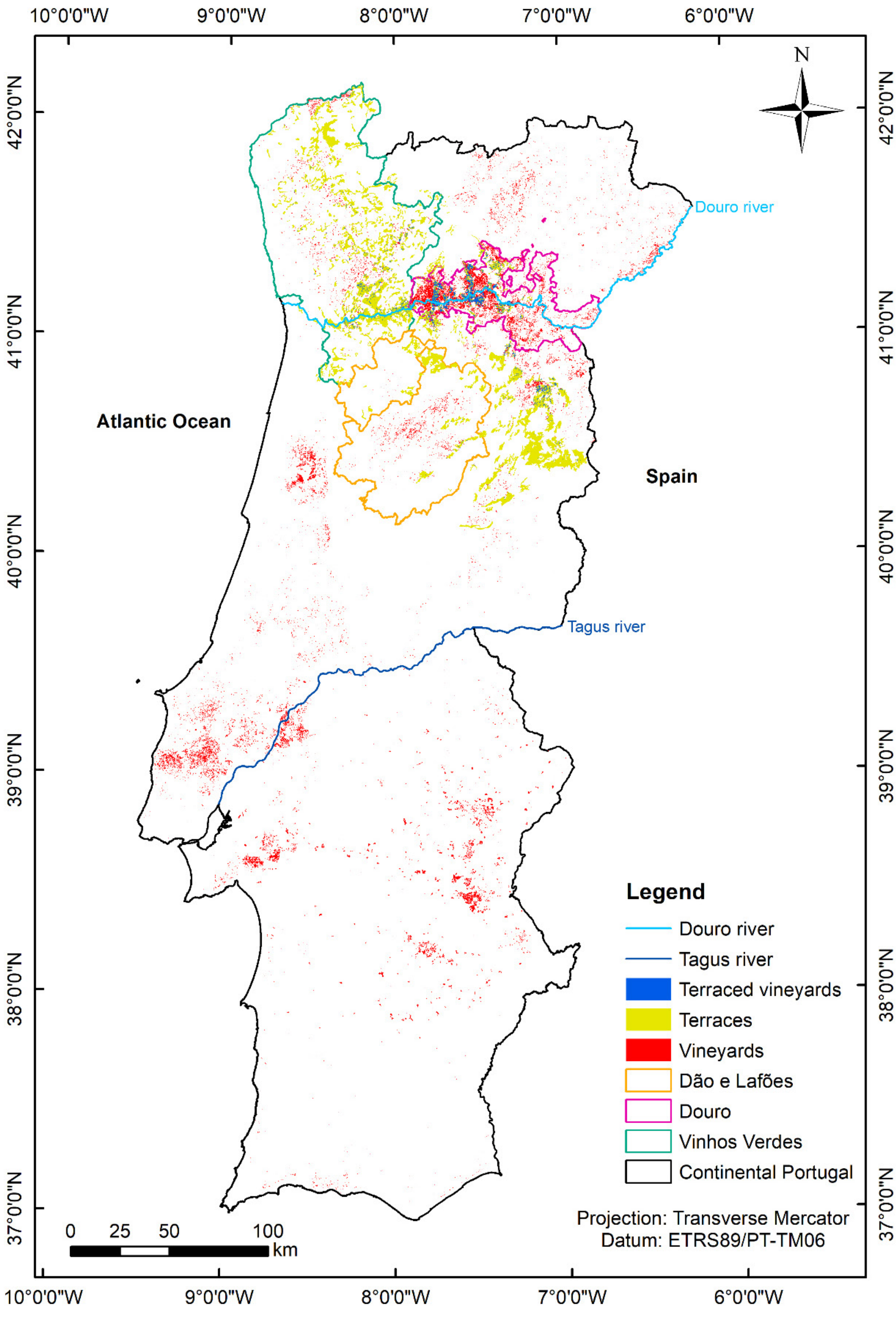

Figure 1. Terraces, vineyards and terraced vineyards in Continental Portugal, with main Wine Regions of the central and northern mountain and steep sloping areas.
Sources of geo-data: Vineyards – COS 2015 (DGOT, 2019b), Terraces – Leitão & Silva, 2013; Wine Regions of Vinhos Verdes and Dão e Lafões– CAOP 2018 (DGOT, 2019a), DL 10 (1992), P 155 (2014); Douro Wine Region – IVDP (2019a).
Figura 1. Terrazas, viñedos y viñedos en terrazas en Portugal continental, con las principales regiones vitivinícolas de las montañas del centro y norte del país, y las zonas de pendiente pronunciada.
Fuentes de datos geográficos: Viñedos - COS 2015 (DGOT, 2019b), terrazas - Leitão y Silva, 2013; Regiones vitivinícolas de Vinhos Verdes y Dão e Lafões– CAOP 2018 (DGOT, 2019a), DL 10 (1992), P 155 (2014); Región vinícola del Duero - IVDP (2019a).

Table 1. Area distribution of terraces, vineyards and terraced vineyards in Continental Portugal and in the main Wine Regions of the central and northern mountain and steep sloping areas (obtained from georeferenced data, Figure 1).
Tabla 1. Distribución del área de terrazas, viñedos y viñedos en terrazas en Portugal continental y en las principales regiones vitivinícolas centrales y septentrionales en zonas de montaña y de pendiente pronunciada (obtenida de datos georreferenciados, Figura 1).

Feature	Wine Regions			Continental Portugal
	Dão e Lafões	Douro	Vinhos Verdes	
	Area (km^2)			
Total	5149.59	2474.03	8383.82	89102.14
Terraces	218.07	293.72	1183.08	2583.61
Vineyards	74.56	604.04	152.6	1890.55
Terraced Vineyards	2.13	140.84	45	226.53
	% of Feature in Total area for each Region			
Terraces	4.2%	11.9%	14.1%	2.9%
Vineyards	1.4%	24.4%	1.8%	2.1%
Terraced Vineyards	0,0%	5.7%	0.5%	0.3%
	% of Region in Continental Portugal for each Feature			
Terraces	8.4%	11.4%	45.8%	100%
Vineyards	3.9%	32.0%	8.1%	100%
Terraced Vineyards	0.9%	62.2%	19.9%	100%

The paper aims at presenting a perspective on soil and water management improvements required for Douro terraced vineyards, answering actual responsibilities determined by the UNESCO World Heritage statute in preserving a cultural, living and evolutional landscape. In so doing, the paper also aims at contributing for a specifically oriented insight on terraces and viticulture of the Douro, a Region surprisingly absent in international scientific literature on those topics (Varotto *et al.,* 2019).

2. The Douro Wine Region

2.1 Historical background

The Douro Wine Region is the oldest demarcated and regulated region in the world, dating back in the mid-XVIIIth century (1756) the first demarcations, determined by *Sebastião José de Carvalho e Melo, Marquis of Pombal*, minister of *King José I* (Figure 2). Nowadays, the Douro Demarcated Region (RDD) has its limits established by the Statute of Designations of Origin and Geographical Indication of Douro Demarcated Region (DL 173, 2019).

Vineyards in the area are reported since Roman times (e. g., Almeida & Almeida, 2004) and in the Middle Age several Cistercian monasteries were set in the Region contributing to promote viticulture and enlarge vineyards area (e. g. Sebastian, 2018). The oldest vineyard stone walled terraces still present in Douro landscape are called *mortórios*, a name literary meaning dead ground and a reference to the *phylloxera* times, at the end of the XIXth century, when, together with other wine regions all over Europe, Douro vineyards were extensively affected and viticulture threatened to extinction (Magalhães, 2008).

2.2. Bio-physical setting

RDD extends eastwards along the Douro River Valley to the Spanish border, in an irregularly distributed strip on both banks that includes the Douro tributaries, especially in the northern bank. Covering around 250 thousand hectares, the area is planted with about 40 thousand hectares of vines, in a mosaique combining permanent crops as olives and almonds, scrublands and other less represented land use types (DGOT, 2019b).

In the morphology of the Douro Wine Region three elements are distinguished: the deep incision of the valleys, with narrow alluvial areas; the very steep and long hill-slopes, straight or even convex in profile; the small rounded or almost flattened catchment divides. All these relief features are present in the region, yet softening from downstream (the western sub-region Baixo Corgo) to upstream the Douro River (the central sub-region Cima Corgo and the eastern sub-region Douro Superior). In addition, they reveal a dynamic geomorphological structure determined by the regional base level of the Douro River with strong vertical erosion. The 400 m elevation identifies valley bottoms while crests are found above 700 m. Minimum elevation is less than 50 m on the Douro River in the west and maximum reaches about 1400 m in *Serra do*

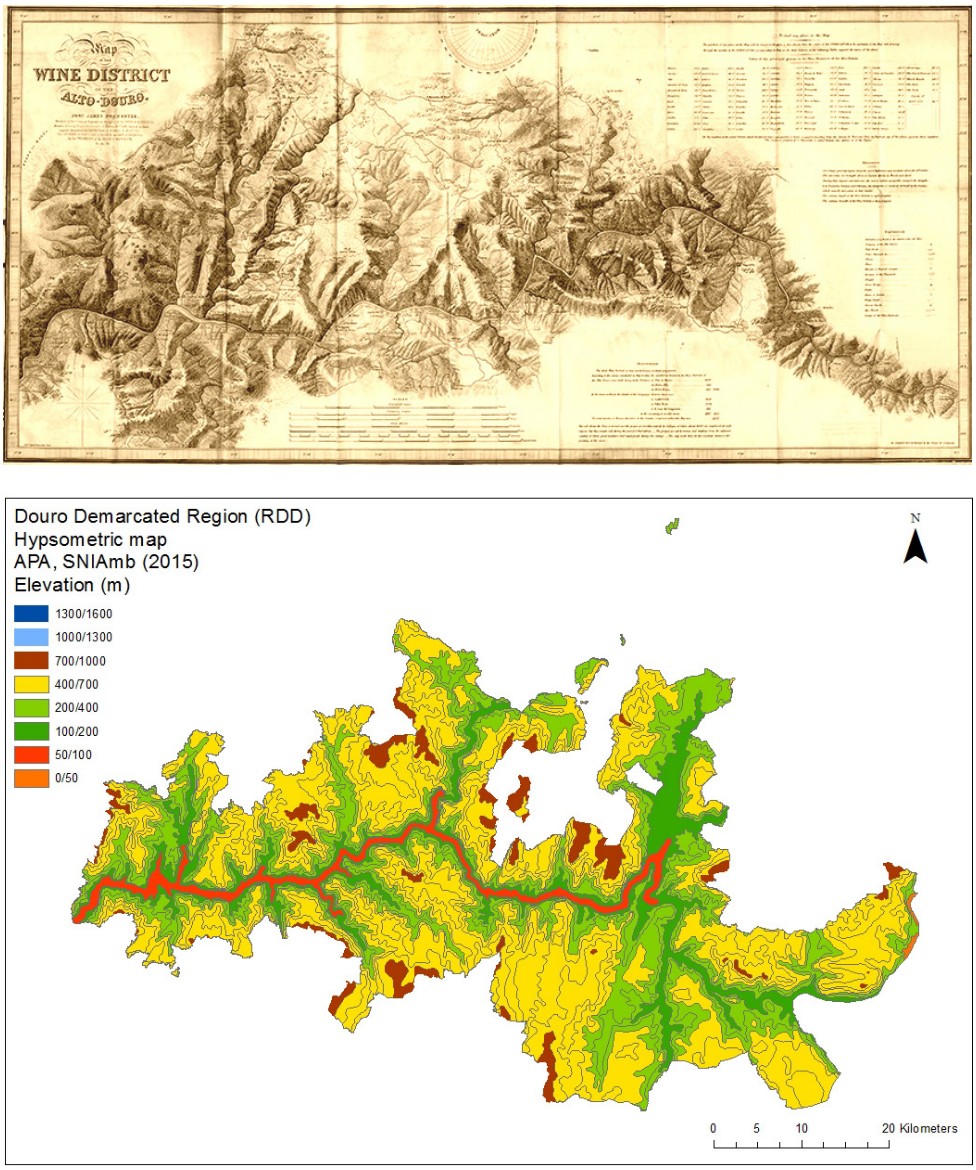

Figure 2. The Douro Wine Region: a mid-XIX[th] century map (Baron of Forrester, 1809 – 1861) (top), and a hypsometric map (bottom, elevation in meters)
Top source: http://portugalpatrimonios.com/tag/regiao-demarcada/;
Bottom source: geo-data from APA, SNIAmb (2015); Figueiredo (2015).

Figura 2. La región vitivinícola del Duero: un mapa de mediados del siglo XIX (Barón de Forrester, 1809-1861) (arriba) y un mapa hipsométrico (abajo, elevación en metros)
Fuente superior: http://portugalpatrimonios.com/tag/regiao-demarcada/;
Fuente inferior: datos geográficos de APA, SNIAmb (2015); Figueiredo (2015).

Marão, a peak along the northern border of the Region (Figueiredo, 2015) (Figure 2).

The climate is Mediterranean with continental and altitudinal influences that, respectively, sharpen and smoothen the summer soil water deficit and the annual thermal amplitude typical of that climate type (Agroconsultores & Coba, 1991). Considering the Aridity Index as a differentiation criterion (ratio between the annual averages of precipitation and potential evapotranspiration), regional climates range from semiarid in the valley bottoms and in Douro Superior, at east (lower elevation, higher continental effect), to wet sub-humid in Baixo Corgo, at west (higher ocean effect) and in the higher elevations, while Cima Corgo sub-region is under dry sub-humid climate (PANCD, 2014; Figueiredo, 2015).

The geological basement is dominantly schist (Pre-Cambrian and Silurian), with more than half of the area. Granites of Variscan orogeny also outcrop in more than 1/3 of the area (Agroconsultores & Coba, 1991). Incipient soils dominate in RDD, imposing strong limitations to crop production. In fact, only Cambisols have a profile with some degree of pedogenetic evolution (12% of RDD area; major soil groups defined according to legend of FAO/UNESCO, 1987). Leptosols, covering almost 60% of the Region, are shallow, with incipient profile development. Soils are generally very stony, acidic and poor in organic matter. The Region is characterized by the extensive representation of Anthrosols (almost 30%), associated with Douro viticulture, although not exclusive to this crop as they are also common in olive and almond groves (Figueiredo, 2013; Figueiredo, 2015; Agroconsultores & Coba, 1991).

2.3. Vines and Wines

The Port is the benchmark of Douro Wine Region. Taking as reference 2018, ca. 80 million liters Port Wine were produced, together with 40 million liters of other wine types also produced in RDD. Furthermore, the Port Wine market is very active and very much oriented to export. In fact, for 2018, total wine sales in RDD summed 555 M€, 65% export. Port Wine sales alone corresponded to 66% of that value, 80% of which was exported. Port contributed to 85% of the RDD wine export and to 53% of the RDD wine sales (IVDP, 2019b).

Douro and Port Wines sector involved, in 2018, more than 1300 economic actors (IVDP, 2019b) dedicated to winemaking, storage, bottling and their combinations. Farms in Douro are about 20 thousand (20,370), with 2.1 ha average size, meaning a production based on very small farms that are also very much spread in space, since the average number of plots per farm is 5.4 and the average plot size is 0.4 ha. However, farms' area distribution is very much asymmetric, as 42% of the farms have less than 0.5 ha and cover only 5% of the RDD area, while those with less than 10 ha represent 96% in number and 58% in area. Farms with more than 20 ha are about 1% of the total number and account for 27% of the RDD area (IVDP, 2019b). In summary, while landownership and wine market actors are very much concentrated, grape production is very much fragmented and spatially spread in many plots.

Since the work by Moreira da Fonseca in the mid-XXth century, vine plots are classified according to their potential for wine quality and the classification assigns the share of grape yield allowed to be included in Port Wine making, 100% for the best ranked (class A). Percent share according to plot class are annually defined. Plot classification is legally regulated (P 413, 2001) and depends on a series of local factors grouped in 3 main criteria – Climate, Soil and Cropping conditions –, differently weighted and scored within a defined range, which may include negative (depreciation) points. As an example, 35% weight in plot classification is assigned to altitude (with a score range from -900 to +240 points), 15% to soil parent material (-400 to +100) and 9% to grape variety (-150 to +150). The system is source of debates and a revision process is ongoing (e. g. Abade & Guerra, 2008), but it keeps its reference status in the region. Besides, it is a framework for vineyard classification that represents a very much *avant la lettre* approach to the nowadays common *terroir* concept. In fact, designed for a so large and diverse Wine Region as the Douro, it keeps the focus, as it should, on the plot scale.

In the Douro Region a large list of grape varieties exists, and these are classified as recommended or authorized, in each case ranked according to their potential quality for wine production. The ranking has implications for the Port Wine production as the very good varieties have a share of 60% or more and the good varieties a share of 40% or less. The list includes white and red grape varieties, with a shorter share for the whites. Touriga Nacional, Tinta Roriz, and Touriga Franca are among the best qualified and the most planted red varieties (e. g. Abade & Guerra, 2008).

3. Terraces and terracing in the Douro

3.1. Terracing and the formation of Anthrosols

Land preparation for vineyard installation on previously uncultivated area, usually covered by Mediterranean scrubland, converts into Anthrosols the original Leptosol by deepening the limiting bedrock layer from about 30 cm to about 1 m or more. The operation breaks the rock layer, fragmenting it to a particle size sufficiently small to allow cultivation while producing some fine earth (silt and fine sand size). Also, the operation promotes mixing of the original shallow soil with the new fragmented rock material. Thus, the main changes in soils determined by these operations are (Figueiredo, 2015):

- Increased effective soil depth;
- Profile uniformity with a new C horizon practically as thick as the soil itself;
- Formation of an A horizon (actually Ap because cultivated) in parallel with the development of the vineyard, initially almost indistinct;
- Very substantial increase in profile stoniness, also very evident at the surface;
- Reduction in organic matter content (which may be around 8% on average in NE Portugal scrubland; Figueiredo, 2013), by mixing the original A horizon with the underlying mineral fraction (without organic matter);
- Disruption of original soil aggregation with restoration of new soil structure in parallel with the development of the vineyard.

The degree to which these changes occur depends on several factors:

- Preceding land use, as shrubs do not correspond necessarily to a native ecosystem but rather to a transitional plant succession departing from an ancient agricultural or even viticulture use;

- Intensity of the intervention, especially noticed when followed by terracing operations, with very important earthmoving volumes;
- Characteristics of the original underlying bedrock, when relatively soft yielding small sized coarse fragment, when relatively hard resulting in significant amounts of larger coarse elements.

3.2. Terrace types

Terraces evolved through time in the Douro and actual landscapes depict side by side structures built up with different models representing periods of the Douro viticulture historical evolution. As a living and evolutional cultural landscape, Douro is constrained to preserve such heritage and, at the same time, develop viticulture and the wine sector in support of its economy and social structure.

Terraces in the Douro may be split in two main types: the old ones, with drystone walls, handmade with large labour inputs, built up until the 30's of the XXth century; the recent ones, with earthen risers, involving heavy machinery in their construction that started in the 70's of last century. In each group, models changed through time.

The oldest remaining model is the pre-*phylloxera* type, with small bench hardly accommodating a vine row. As the name indicates, these terraces were the common model before the *phylloxera* pest invaded the Region in the late XIXth century, devastating viticulture and leading to large abandoned terraced areas, still present in Douro as *mortórios*. The recovery of Douro viticulture is represented by the post-*phylloxera* terraces. These had much larger benches, leaned downhill, forming geometrically regular vineyard plots with more than 10 vine rows. Drystone walls could be very high in very steep slopes, where also benches were shortened, and they were rectilinear in shape, replacing the former curvilinear shape that closely follows the topographical contour. Angular breaks divided walls in sections so as to fit to the natural hillslope form.

Mechanized soil preparation for vineyard plantation brought new terrace models where major changes were the replacement of the former vertical drystone wall by an earthen riser and the adoption of a levelled bench. The large or wide terraces built up extensively in the 70's of last century, accommodated two vine rows. As no restriction existed in what concerns slope gradient of the future vineyard plot, large tracts with very steep slope were planted applying the model. In such topographical conditions and with a fixed bench width, terraces had very high risers and low effective productive area (the bench with two vine rows placed in its inward and outward edge). This lead to high exposure of bare risers to erosion. Rills are commonly observed in such risers and, in cases, terrace collapse occurs during heavy rainfalls. In low frequency intense and long rainfall periods, collapses propagate downhill, forming gully size incisions on a sequence of terraces along the slope (Fernandes *et al.,* 2017). Following, in the 1990's, a new model was recommended for the steeper slopes, shortening the bench width and, consequently, reducing risers' height: the single vine row narrow terraces. Systematic observation indicates that erosion features are much less present on these narrow terraces than on the earlier wide terraces.

It should be added that an important part of Douro vineyards is not terraced. In most cases, vine rows roughly align with the contour and the inter-row area is kept with the original hillslope gradient, a situation that is uncomfortable for performing crop operations including harvesting. Alternatively, vine rows may be planted perpendicular to the contour, thus with the natural hillslope gradient, a model named *vinha ao alto*. Introduced in the Region in the 1980's, this plantation system is present in about 20% of the vineyards area. Among other advantages, it allows higher vine plant density than the remainder models (Bianchi-de-Aguiar, 1987). This apparently non-conservative model actually yields low soil and water losses due to the effective surface protection against rainfall impact provided by the high soil stoniness (Figueiredo, 2001; 2012; Figueiredo *et al.,* 2013).

A set of images of Douro terraces is depicted in Figure 3 and the above description of Douro vineyard terraces may also be found in a wide range of scientific, technical and cultural sources (e. g. Bianchi-de-Aguiar, 2002; Pedrosa *et al.,* 2004; Fauvrelle, 2007; Magalhães, 2008; Figueiredo, 2015).

3.3. Preservation and change in Douro terraced viticulture: regulations and funding programmes

Following the World Heritage status granted by UNESCO to the Region in 2001, a set of scattered regulations were assembled in a single legal document, a Governmental Resolution (RCM 150, 2003) that consolidates information regarding vineyard plantation systems in the Douro Region. The typology of the several plantation systems accepted in Alto Douro Vinhateiro, together with their associated normative implementation guidelines, were stated in that Resolution and are summarized as follows.

- Micro-terraces - a small horizontal bench, perpendicular to the slope direction, up to 1 m wide, established in vine inter-rows, vines rows being installed on the riser at the original land level.
- Narrow terraces - horizontal bench, less than 2.5 m wide, where vine rows are planted in the downslope edge, with earthen riser.
- Wide terraces - horizontal terraces, more than 2.5 m wide, where two or more rows of vines are planted.
- *Vinha ao alto* - vineyard planted in rows parallel to the natural slope, with uniform slope gradient, intersected by roads built-up during vineyard installation.

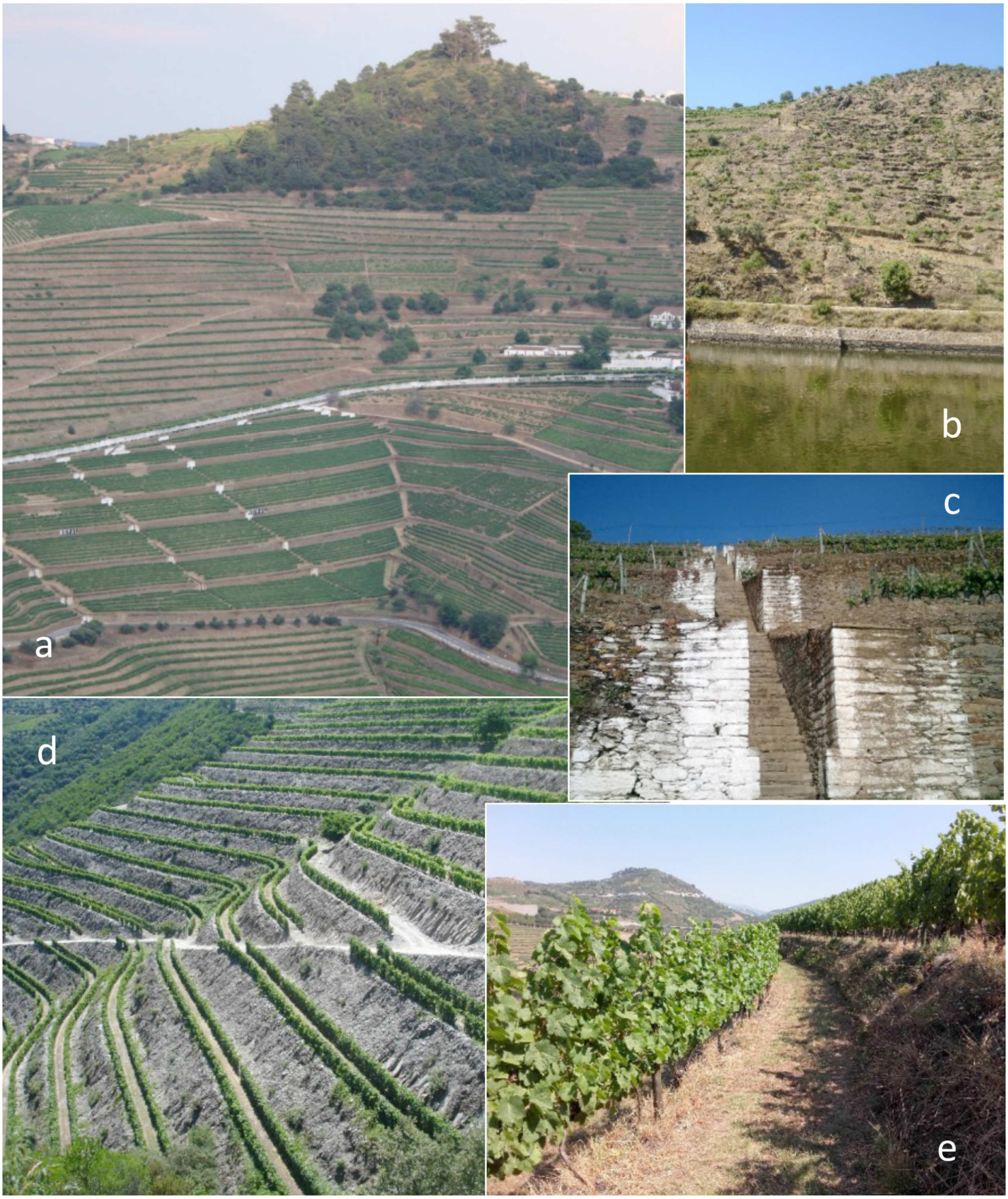

Figure 3. Terraced vineyards of the Douro Wine Region: (a) old and recent terraces side by side with the post-*phylloxera* model at the centre; (b) *mort*órios or abandoned pre-*phylloxera* terraces; (c) post-*phylloxera* drystone walls and stairs; (d) recent wide two vine row terraces; (e) recent narrow single vine row terraces (Photos by Figueiredo).

*Figura 3. Viñedos en terrazas de la región vitivinícola del Duero: (a) mosaico de terrazas antiguas y recientes, con el modelo post-filoxera en el centro; (b) mort*órios *o terrazas abandonadas de pre-filoxera; (c) muros y escaleras de piedra seca post-filoxera; (d) terrazas recientes y amplias de dos hileras de vid; (e) terrazas recientes y estrechas de una sola hilera de vid (Fotos de Figueiredo).*

The normative guidelines for the installation of new vineyards consider three criteria: slope gradient, former land use, existing drystone structures. Slope gradient thresholds are 50%, 40% and 30%. Existing drystone walls have to be kept intact when planting the new vineyard. Guidelines apply strictly to new vineyards plantation on natural or agricultural areas.

- Vineyards plantation on slope gradient higher than 50% is prohibited, except when the new vineyard replaces either (i) a former vineyard or olive grove with drystone walls or *mortórios*, the new vineyard having to be installed in micro-terraces, keeping drystone walls intact; or (ii) a former olive or almond grove or other crops, in which case either narrow or micro-terraces are accepted.
- Vineyards plantation on slopes gradient ranging from 40% to 50% may be accepted on narrow or micro-terraces, except where the new vineyard replaces former vineyards or olive groves with drystone walls or *mortórios*, in which case narrow or micro-terraces have to accommodate to the existing structures and these have to be kept intact.
- Vineyard plantation on slope gradients lower than 40% is unrestricted, except where the new vineyard replaces former vineyards or olive groves with drystone walls or *mortórios*, in which case it will have to be planted in narrow or micro-terraces, keeping the drystone structures intact.
- *Vinha ao alto* can only be planted on slope gradients lower than 40%, except for the *Extremadouro* landscape unit (a specific landscape unit in the Region), where the upper limit is 30%.

An important RDD vineyard area was re-structured in the last three decades, summing up 23 thousand hectares between 1985 and 2014. The main effort to adapt vineyards to better plantation systems and terrace models was done in the period 2000-2007, when ten thousand hectares were restructured under the Vitis programme. Six thousand more were re-structured between 2008 and 2014 under five consecutive RARRV programmes. Specific EU funds supported the mentioned operations, which applied to more than half of the actual vineyards area (IVDP, 2019b). Non-productive interventions were also supported. The most evident example is the rehabilitation of drystone structures, including terrace walls or farm buildings, financed through a programme managed by a specific local body of the Northern Region Agriculture Directorate (ELA - DV; P 261, 2015) .

4. Challenges to Douro terraced vineyards: soil and water management, research and development prospects

4.1. Critical areas and critical issues

Among the threats to the soil resource in the Region, the major one is water erosion, potentially severe under such natural setting, characterized by steep slopes, concentrated rainfalls typical of the semiarid and dry sub-humid Mediterranean and weakly aggregated silt-loam soils (Figueiredo, 2001; 2013). In fact, 56% of the area is under potential moderate or higher risk and 29% under severe and very severe risk (Figueiredo, 2015). This threat affects about 15% of European soils and is highly represented in mountain and sloping agri-environments, especially in permanent crops (Thematic Strategy for Soil Protection in Europe, COM, 2006). Among these, vineyard rank high in soil loss records in the Mediterranean Europe, yet with a wide range of erosion rates (Maertens *et al.,* 2012; Cerdan *et al.,* 2006), for instance, in a Douro vineyard planted in rows perpendicular to the contour (a non-conservative system) average soil loss was low due to high soil stoniness (Figueiredo *et al.,* 1998; Figueiredo, 2013).

While traditional dry stone structures are a heritage to be kept preserved, as conservation measures fully tested trough time, changes ongoing in Douro rise concerns with soil and water management and conservation in the more recent terraces and plantation systems. These have a flat bench and a bare earthen riser. In any case, terraces impose changes in the natural surface and subsurface hydrology, especially considering the steep and long hillslopes where vineyards are planted. The drainage network in vineyard planted hillslopes is artificial and commonly matches farm's road network. In this context, from the soil and water management and conservation perspective, areas critically susceptible to soil and water losses by erosion are the bare surfaces exposed to rainfall, meaning: (i) the inter-row lanes (between vine plant rows) when conventionally managed; (ii) the terrace risers; (iii) the road / drainage network (Figueiredo, 2015). At vineyard scale, improvements in system's performance in soil and water management and conservation should focus on these critical areas and, for actual Douro vineyard plantation systems, interventions can be tuned according to the scheme proposed by Figueiredo (2015). As shown in Table 2, inter-row lanes in terraced vineyards are not critical (as terrace benches are flat), while *vinha ao alto* (with rows perpendicular to the contour) represent areas most exposed to rainfall erosion. Earthen risers in wide bench terraces also represent a concern, as stated earlier, and the road and drainage network is especially critical in these systems, an issue addressed to in the next subsection.

As well, improvements in soil and water management and conservation should couple erosion control (a critical issue in a mountain and sloping environment with high potential erosion risk) with other critical issues for Douro viticulture. These are the severe summer water shortage, typical of the Mediterranean climate, and the low organic matter content largely prevailing in regional soils (Agroconsultores & Coba, 1991; Figueiredo, 2013; 2015). As widely known, soil water storage capacity is dependent on organic matter content as well as soil aggregate stability and erodibility, and it regulates runoff generation and soil water availability for plant growth.

Table 2. Critical areas management: erosion risk exposure and control interventions (adapted from Figueiredo, 2015).
Tabla 2. Manejo de áreas críticas: exposición al riesgo de erosión e intervenciones de control (adaptado de Figueiredo, 2015).

Vineyard systems installed		**Critical aeas**		
		Inter-row lanes	**Risers**	**Drainage network**
		Risk control requirements		
Original slope, contour rows	Gentle slopes	Low	-	Low
	Steep slopes	High	-	High
Stonewalled terraces	Narrow benches	Low	-	High
	Wide benches	High	-	High
Earthen riser terraces	Narrow benches	Low	High	High
	Wide benches	Low	Very high	Very high
Rows perpendicular to contour		Very high	-	High
		Type of intervention		
Vineyard management interventions		Weed control, soil management	Cover control, repairing	Cleaning, maintaining, repairing

4.2. Soil management in inter-row lanes

The most widely represented threat to soil resource in Europe is the loss of organic matter, affecting about 40% of the surface area of the European Union (COM, 2006). In Mediterranean conventional cropping systems, it is commonly accepted that low plant biomass production combined with dry climatic conditions limit accumulation of organic matter in soils, as a result of low amounts of crop residues generated and of their high mineralization rates (Carvalho, 2013). No-till systems can reduce mineralization rates, due to low soil disturbance, and increase crop residues amounts left over ground, therefore increasing opportunities for organic matter accumulation in soils. However, Carvalho (2013) states that one important additional element to explain soil organic matter increase after no-till systems are implemented is the reduction of erosion losses due to soil protection by residue cover. Soil organic matter increase is relevant for soil quality in view crop production and it is, as well, relevant for the associated soil carbon storage in view actual and global major environmental issues (Lal, 2004).

The most represented soils in RDD (Leptosols and Surribic Anthrosols, 75% of the regional area) have low and very low organic matter content, meaning dominantly less than 1% (Agroconsultores & Coba, 1991; Figueiredo, 2013; 2015). Increasing the organic content of vineyard soils is key for improving vine plant nutrition, increasing aggregate stability and reducing soil erodibility, elements that Carvalho (2013) demonstrates to be achieved with no-till Mediterranean cropping systems, yet not in the short but rather in the medium and long-term. As summer water shortage is critical in the Mediterranean, in permanent crops as vineyards, conventional tillage was targeted in spring weed control based on reducing weeds competition for water with vines on soil water decay period. However, no-till soil management keeping herbaceous vegetation on the vines inter-row lane proved effective in tackling the problem in Douro vineyards as well as in other permanent crops in NE Portugal (Martins *et al.,* 2010; 2011; 2014; Raimundo *et al.,* 2011). In fact, these studies showed that the soil water decay in spring is more relevant in vine plant row than in the grass covered lane between vine rows, in surface layer, meaning that competition weds-vines is harmless early summer onwards, while competition prevailing in spring is beneficial to reduce vine plants vigor and improve grape quality for wine, Moreover, summer vine development depends much more on deep than surface soil layers water content.

Erosion control performance of no-till with different option for managing herbaceous vegetation in the vine inter-row lane was assessed by Figueiredo *et al.* (2017). Increasing herbaceous vegetation cover in from the typical 20% up to 80%, through sowing the inter-row lanes, leads to a soil loss reduction of 24% when compared with conventional tillage. Better results were obtained when the strategy focused on spring rather than winter weed control. Delaying 2 months weed control by clearance (meaning at maximum vine canopy cover) helps reducing soil loss by 52% of the rate found in conventional systems, where spring weed control is performed at start of vine growing season (one month delay leads to a 31% mean soil loss rate reduction). These results show that sowing the inter-row in autumn is not a better option than leaving adventitious vegetation grow free, besides being economically and environmentally more costly. On the other hand, competition for water between vibes and weeds in spring does not seem to be any more under discussion, as indicated above. A third inter-row cover control strategy was appraised in the study by Figueiredo *et al.* (2017), which consists in increasing residue cover left over ground when performing spring inter-row clearance at typical date. In conventional systems, residues are incorporated in the soil surface layer by a tillage operation.

In no-till systems, keeping high level of weed control residues over the inter-row during spring (80% cover) results in a very effective soil loss reduction (74% as compared to conventional, where typical residue cover after weed control is 20%). Besides its erosion control effectiveness, this third strategy is less dependent than the second one on the inter-annual variability of weather conditions and the consequent duration of vines and weeds development periods, commonly imposing stressful intervention decisions to the farmer.

4.3. Road and drainage networks: role in geomorphological and hydrological risks

Erosion research in cropland commonly address the plot or field scale but some studies showed the importance of linear features as rural roads (Tarolli *et al.,* 2015). Figueiredo *et al.* (unpublished data) measured a 15 times higher erosion rate in the road network than in the fields, in a recently afforested area (Figueiredo *et al.,* 2005). The artificialized drainage network is commonly coupled with the road system both corresponding to hydrological connectivity elements in the landscape.

Terraces inadequately projected and built are also risk areas due to landslides (Pereira *et al.,* 2014). Changes in the surface and subsurface water dynamics in terraces determine instability and collapse during heavy rainfalls that saturate the soils, the terrace collapses promoting concentrated overland flow. Research on coupled processes is hardly found in literature, but may help explaining exceptional erosion rates in terraced areas (Ramos & Martínez-Casasnovas, 2009). The areal extent of these recent design terraces in the Douro region leads to slope instability extreme event (Zêzere *et al.,* 2014). Assessment of susceptibility to slope instability, at regional and local scale, has been performed using physically based models (Teixeira *et al.,* 2015; Pereira *et al.,* 2012). Geophysical methods provide in depth study of water dynamics in these very disturbed soil profiles (Samouëlian *et al.,* 2005; Tetegan *et al.,* 2012; Dafonte *et al.*, 2016).

The above mentioned major threats to soil resource are inevitably associated with geomorphological and hydrological risks. The actual hillslope hydrology of large terraced areas is deeply changed and depends on efficient design and adequate maintenance of vineyards drainage network. This regards either surface or subsurface flow along the hillslopes and within the terraced catchments in wet periods and shows the critical role of vineyards drainage networks on hydrological risk in steep sloping terraced areas. Furthermore, extreme episodes, with higher than actual frequency and intensity, are foreseen in the regional climatic context of the present century second half (Jones & Alves, 2012), increasing future agrometeorological hazards that Douro viticulture will have to cope with. Hydrological risks, as floods and droughts, may increase accordingly, following a changing trend also found in other areas of NE Portugal (Okada, 2019; Royer, 2019).

As so, control of excess water in the wet season is critical in terraced landscapes; yet poor attention has been paid to the issue in Douro vineyards. Traditional stone structures are still active waterways draining vineyard areas in the region, but, in most cases, the unpaved roads giving access to farm plots have actually a waterway function during rainfall events. As sediment sources, they contribute to local catchments' sediment load. Newly planted areas, especially in large farms, are increasingly adopting the urban-based design, consisting in buried pipe systems (Figueiredo, 2015). These, however, face a problem infrequent in urban areas, which is the siltation of the pipe system with incoming sediment from the unpaved farm roads, therefore increasing maintenance costs. No actual solution exists or have been consistently tested to cope with the problem.

4.4. Prospecting research responses to the sustainability challenge

Besides natural hazards, Douro viticulture faces as well an increasingly competitive and globalized economic ground, expected to put at increasingly higher stress the socioeconomic structure and activities supporting Douro living cultural landscape (Hogg & Rebelo, 2017). To all such future uncertainties and constraints, the Region has to respond with its historically recognized wise adaptation to changes. This is actually ongoing in the viticulture sector, supported on public policies and funding programmes. Still, research oriented to respond to the region viticulture sustainability challenge is required, with specific emphasis on key resources efficient and conservative use, enabling vinegrowers with scientifically grounded solutions for their farm and plot scale problems. Following, research prospects for filling in prevailing knowledge gaps are outlined.

The soil resource is a scarce asset in RDD. Due to topography and water shortage, typical of Mediterranean mountain and steep-sloping areas, the Douro vinegrowers have to manage a poor pedological heritage subject to threats associated to the natural conditions that land uses and practices may amplify (Figueiredo, 2015). It is a region that depends on the soil for its product of recognized excellence, facing the double challenge of overcoming basic land quality limitations while coping with natural and human induced risks that also threaten the territory.

Soil conservation through the many models developed and tested in the Region will be keeping a central role in Douro viticulture, and refining soil quality appraisal is certainly also a way to better value the territory exploring the wines *terroir* concept. Therefore, technology transfer of scientific advances in these topics should be a priority to cope with the sustainability challenge. This is the case of a framework of soil quality indicators for viticulture and wine quality that should be developed and tested in close dialog between researchers and the regional actors. Following, non-invasive sensing techniques should be developed and tested for specific application in the regional complex terrain context, allowing fast and spatially scaled appraisal of those indicators (e. g., Tarolli *et al.,* 2015).

Water management stands on a similar level as and is inevitably coupled with soil conservation in what regards RDD challenges. As typical of the Mediterranean environments, the Region is a land of extremes, and vine-growers have to tackle in the same year summer water shortage and winter excess. Tuned weed control techniques in vines inter-row are crucial to soil protection against erosion as well as to water management, either in deficit or in excess periods. Adequate control interventions, based on innovative soil water monitoring techniques, again to be refined in the research ground and transferred to the vineyard plot level, can open possibilities to improve water use efficiency in vineyards (e. g. Pôças *et al.,* 2020). Controlling runoff source areas is required as well, to limit the increased hydrological and geomorphological risks that a terraced landscape faces in the wet season. This not only regards the vines inter-row areas but also terrace risers, for which scarce research effort have been poured into the Region and that should be coupled with risers' parallel and insufficiently explored role as functional biodiversity corridors (Carlos *et al.,* 2019).

Finally, with surface and subsurface hydrology entirely changed in terraced hillslopes, drainage networks have to be designed to fast and adequately conveyance of excess water in wet periods, therefore limiting risks. In fact, these associates hydrological risk with geomorphological risk, as changes in topography imposed by land terracing determine also increased risk of mass movements whose importance in magnitude, frequency and damage has been recognized (Pereira *et al.*, 2014; Zêzere *et al.,* 2014; Rodrigues & Pedrosa, 2016). These studies point out the combined effects of surface and subsurface flow convergence during long wet periods triggering the larger erosional episodes recorded in region. As so, hydrological modeling, spatially distributed and accommodating the complexity of runoff paths in terraced vineyards, is required to support better designed drainage networks (e. g. Moussa *et al.,* 2010).

In addition, revisiting traditional building techniques and materials for installing such water control structures opens possibilities for, once again coupling innovation with preservation and move towards better risk- controlled landscapes.

5. Concluding remarks

The Douro vineyards are a striking example of soil protection materialized in a strongly humanized landscape, where terraces cover a large part of the region. Side by side, old drystone wall terraces and recent earthen riser terraces depict a historical struggle for taking advantage of a harsh environment with meager natural resources. Generations fought for keeping soil and water where they are most needed: soil in place and water in soil, in the layers that vine roots explore to outcome an excellence product: the Port and Douro wines. In fact, this was the key solution for sustainable resource use, issued from hard work and also from wise reasoning.

The recognition of *Alto Douro Vinhateiro* as a UNESCO World Heritage in 2001 increased responsibilities of actors and authorities in preserving their highly valuable heritage while ensuring that the new plantation models are able to couple conservative resource use (an asset of Douro viticulture) with actual requirements for economic sustainability and social wealth. In this line, efforts should be directed to the critical risk areas of the new terraced vineyards, applying protection measures in the terrace benches, in the bare earthen risers and in the drainage network. Innovative soil and water management practices have to be developed on the scientific ground, locally tested, keeping close dialog between researchers and regional actors for effective technology transfer.

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