An overview of the recent approaches for terroir functional modelling, footprinting and zoning

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Abstract

Notions of terroir and their conceptualization through agro-environmental sciences have become popular in many parts of world. Originally developed for wine, terroir now encompasses many other crops including fruits, vegetables, cheese, olive oil, coffee, cacao and other crops, linking the uniqueness and quality of both beverages and foods to the environment where they are produced, giving the consumer a sense of place. Climate, geology, geomorphology, and soil are the main environmental factors which compose the terroir effect at different scales. Often considered immutable at the cultural scale, the natural components of terroir are actually a set of processes, which together create a delicate equilibrium and regulation of its effect on products in both space and time. Due to both a greater need to better understand regional to site variations in crop production and the growth in spatial analytic technologies, the study of terroir has shifted from a largely descriptive regional science to a more applied, technical research field. Furthermore, the explosion of spatial data availability and sensing technologies has made the within-field scale of study more valuable to the individual grower. The result has been greater adoption but also issues associated with both the spatial and temporal scales required for practical applications, as well as the relevant approaches for data synthesis. Moreover, as soil microbial communities are known to be of vital importance for terrestrial processes by driving the major soil geochemical cycles and supporting healthy plant growth, an intensive investigation of the microbial organization and their function is also required. Our objective is to present an overview of existing data and modelling approaches for terroir functional modelling, footprinting and zoning at local and regional scales. This review will focus on two main areas of recent terroir research: 1) using new tools to unravel the biogeochemical cycles of both macro- and micronutrients, the biological and chemical signatures of terroirs (i.e. the metagenomic approach and the regional fingerprinting); 2) terroir zoning at different scales: mapping terroirs and using remote and proxy sensing technologies to monitor soil quality and manage the crop system for a better food quality. Both implementations of terroir chemical/biological footprinting and geospatial technologies are promising for the management of terroir units, particularly the remote and proxy data in conjunction with spatial statistics. As a matter of fact, the managed zones will be updatable and the effects of viticultural and/or soil management practices might be easier to control. The perspective of facilitated terroir spatial monitoring makes it possible to address another great challenge in the years to come: the issue of terroir sustainability and the construction of efficient strategies for assessing and applying them across numerous scales.

1 Introduction

The keyword ‘terroir’ in the Scopus database leads to identifying 385 papers published from 1980 to 2014 (September) including a steady rise from 2005 to 2014. This trend provides evidence of the ever-growing interest of the scientific community in understanding the characteristics and relationships between the many factors of terroir. “Terroir” is a French word, meaning delimited areas with homogeneous environmental features that are likely to confer typical wine qualities identified through collective memory and conveyed from generation to generation within a territory marked by social context and cultural technical choices (Vaudour, 2002, 2003). The tradition of terroir wines has strong cultural connections, referring to traditions of good drinking, of farming and producing typical wines that are rooted in a region or made from specific places with organoleptic features easily recognizable from other wines from other regions. In France these are sometimes named "crus", "clos" and, in the case of Burgundy, "climats". The making of a typical wine originating from a given terroir unit implies that fields or subfields be assigned to this unit for merging grapes of one or several specific varieties into containers within a winery: as such winegrowing terroirs need to be managed across the geographical space. Both Greek and Latin agronomists developed and used recommendations for the spatial management of terroirs, as exemplified by the Amos farming leases dating back the High Hellenistic period. These leases discriminated between vineyards planted on the “plains” and vineyards planted in “rocky terrains”, with differing prescriptions for vineyard planting densities (Vaudour and Boulay, 2013). Inherited from medieval times and monasteries, high resolution grapevine selection from small-sized fields of some hundreds of square meters has long been practiced for the making of famous crus in small volumes (barrels of 200 hl) (Dion, 1990; Unwin, 1994). In that sense, the shaping of terroirs results from a long heuristic process (likely hundreds of years) through History marked with discontinuities due to wars, spread of plagues, and wine market opportunities. For centuries, such heuristic processes have mostly been carried out on less fertile soils (fertile soils being reserved to annual crop cultivation) and without resorting to irrigation, thus accentuating multi-year variability due to vintage weather (“millésime” effect). As an entity distributed over space and time, terroir has cultural aspects that have heritage, landscape, and reputation value-added components (Tomasi et al., 2013), that come from historical empirically-derived technical adjustments, the transmission of taste typicity over generations, and strong gastronomical traditions. On the other hand, the agro-environmental aspects of terroir are likely to be conceptualized, in order to characterize, delineate and monitor zones with homogeneous or outstanding grape and/or wine, soil, geomorphological, geological, landscape, and climate characteristics at a given spatial level and over a given duration. This process may be in the nascent stages of understanding vineyard spatial management in young winegrowing regions, or refined in those winegrowing regions with long-lived wine traditions.

At the international scale, a definition focused on the agro-environmental facets of terroir was adopted in 2010 by the International Vine and Wine Organization (resolution OIV/VITI 333/2010). Originally developed for wine, approaches for defining terroirs are now being carried to other specialty crops such as coffee (e.g., De Assis Silva et al., 2014), tea (e.g., Besky, 2014), tequila (Bowen and Zapata, 2009), honey, maple syrup, cacao, olive oil, fruits, vegetables, and cheese (Trubek, 2008; Jacobsen, 2010), ultimately linking the uniqueness and quality of both beverages and foods to the environment where they are produced. The trend for providing the consumer a sense of a place has historically developed alongside the legal protection of these products, through either “Protected Designations of Origin” (PDOs) or Protected Geographical Indications (PGIs). However, although they both rely on the assumption of a deterministic relationship between food quality and agro-environmental features, legal definitions of PDOs and PGIs are not always spatially representative of the terroirs they come from. In the European Union for instance, PDOs refer to the names of regions, given areas or even countries assigned to agricultural crops or value-added products which are produced, processed or prepared in a region according to traditional methods. In France, Italy and Spain, official PDOs that provide terroir wines legal protection from falsified wines coming from other areas date back to 1935 (Vaudour, 2003). However, there have been many historical precursors of PDOs, such as, Chianti in the XVIIth century (Tomasi et al., 2013) or in the XIXth century Jerez (Cabral Chamorro, 1987) and Champagne (Marre, 2004). Under a PDO, wine-growers, wine-makers and experts jointly define those zones that are warranted to produce wines named after their most renowned places, under common producing rules considered as traditional. These zones are generally based on pre-existing boundaries of administrative districts or easily demarcating patterns derived from hydrological networks, roads or railways. In contrast, PGIs refer to the names of areas with some linkage to product quality with at least one of the stages of production, processing or preparation occurring in the considered area. Despite differing definitions, terroir is sometimes confused with PDOs or may even be confused with PGIs (Barham, 2003), when one or, more likely, several terroir units may constitute the delimitated areas within the PDO, be included in them, or even intersect them.

Whatever winegrowing region in the world, either valuing inherited management zones, or attempting to construct them, the so-called “natural” components of terroir actually result from a set of processes, which together with viticultural practices create a delicate equilibrium and regulate its effect on products in both space and time (Van Leeuwen et al., 2004; Deloire et al., 2005; Van Leeuwen and Seguin, 2006; Costantini and Bucelli, 2014). At its most basic understanding, the so-called “concept of terroir” relates the sensory attributes of wine to the environmental conditions in which the grapes are grown (Van Leeuwen and Seguin, 2006; White et al., 2007; Tempesta et al., 2010).

Given the economic importance of the wine industry worldwide, there is clearly a need to better understand the spatial and temporal variability of grape composition and which spatial and cultural scales and resolutions are best suited to manage the production of terroir wines that reveal the typical qualities of terroir units across a given territory, together with minimizing the environmental impacts of this production. Underlying notions for such questioning stem from two main research areas: first, the concepts and knowledge on agro-ecosystems raised and revisited for present-day agriculture, which faces an increasing number of challenges, and the prospect to ensure various ecosystem services by means of implementing agro-ecological practices (Doré et al., 2011; Wezel et al., 2014); second, concepts and approaches on digital soil assessments based on pedometrics and/or proxy-remote sensing techniques (Carré et al., 2007; Minasny et al., 2012; Werban et al., 2013; Hartemink and Minasny, 2014). These challenges go hand in hand with the need for an interdisciplinary approach of soil (Brevik et al., 2015). There is a greater need to understand regional to site and site to regional variations in crop production and the growth in spatial analytic technologies is likely to facilitate downscaling and up-scaling approaches to address these needs. Together with the emergence of precision viticulture, the explosion of spatial data availability and geospatial technologies in the past 15 years have made the within-field/farm scale of study more valuable to the individual grower, resulting in greater adoption and application (Tomasi et al., 2013). Furthermore, the study of terroir has shifted from a largely descriptive regional science back to the 1990s to a more applied, technical research field at the beginning of the XXIth century. Confusion between PDOs and terroir, and the strict observance of no irrigation, according to historical heuristic processes of terroir, result in misleading questions such as the possible compatibility of terroir and precision viticulture (Bramley and Hamilton, 1997). However, the long process of terroir identification over time questions those practices that enhance or diminish terroir sustainability, particularly in recent times with the advent of modern viticulture. For example, viticultural soils appear to be exposed to degradation processes, perhaps more than ever because of improper practices of land management (Blavet et al., 2009; Follain et al., 2012; Costantini and Lorenzetti, 2013). In addition, soil contamination by copper resulting for the cumulated use of Bordeaux mixture and other copper fungicides is an increasing issue (Pieztrak and McPhail, 2004; Fernández-Calviño et al., 2013; Chopin et al., 2008; Mirlean et al., 2007, 2009; El Hadri et al., 2012; El Azzi et al., 2013) and appears to result in modifying the spatial distribution and composition of soil microbial communities (Jacobson et al., 2007; Mackie et al., 2013). Because of water scarcity, irrigation may be practiced with saline water or saline effluent with possible deleterious effects on plant growth (Paranychianakis and Angelakis, 2008; Walker et al., 2009; Stevens et al., 2010, 2011) and on soil salinity, structure and quality (Crescimanno et al., 2007; Urdanoz and Aragüés, 2009). Thus, an intensive investigation of the microbial and fungal organization and their function is required, as soil microbial and fungal communities are known to be of vital importance for terrestrial processes by driving the major soil geochemical cycles and supporting healthy plant growth (Nannipieri et al, 2003; Bokulich et al, 2014).

Our objective is therefore to present an overview of existing data and analytical/modelling approaches for the footprinting and zoning of terroirs at local and regional scales. This review will focus on two main areas of recent terroir research: 1) new tools for assessing terroir footprints, comprising metabolomics, the metagenomic approach and microbial/chemical fingerprinting; 2) terroir zoning at different scales, using remote and proxy sensing technologies to spatially manage the crop system for higher quality and the spatial monitoring of soil quality.

1 Emerging tools for assessing terroir footprints

1.1 Chemical fingerprint and metabolomics

Wines from distinct countries or regions can be discriminated through their chemical composition and/or sensorial profiles. A recent study quantifying a large number of elements (33) in wine and soil samples analysed by quadrupole inductively plasma mass spectrometry (Q-ICPMS) in addition to $^{87}Sr/^{86}Sr$ isotopic analysis allowed for differentiation among wine-producing regions of Argentina (Di Paola-Naranjo et al., 2011). In this case the $^{87}Sr/^{86}Sr$ ratio was amongst the best discriminators and the value ranges of which were similar between soils and wines. This corroborates the results obtained by Marchionni et al. (2013) across six distinct wine appellations in Italy, but in their study they focused on parent material and this ratio matched those observed for homogeneous soil parental material such as volcanic rocks. Studying the whole parent material-soil-plant-wine chain at a single rainfed vineyard located in the volcanic area of Campi Flegrei (Southern Italy), and considering both a set of putative rare earth elements geotracers and the Sr isotope ratio, Mercurio et al. (2014) found that only this isotopic ratio was "consistently and inherently transferred and maintained from geologic parent material to wine, through soil horizons, branches, leaves, and grapes". However, considering several vintages, Marchionni et al. (2013) observed that wines showing Sr isotopic ratios matching those of the underlying substrates were mostly originating from vineyards grown on volcanic rocks, unlike wines from vineyards on sedimentary or granitic rocks. As isotopic ratios of geological substrates belonging to different geological districts may partially overlap, Mercurio et al. (2014) recommend assessing the isotopic ratios together with a pertinent soil classification for a reliable assurance of wine provenance. Geographical fingerprinting of wines may also apply at distances as short as 4 Km. Research by Tarr et al. (2013) found that more than a thousand components were identified from high performance liquid chromatography of juices from two varieties (Syrah and Grenache) originating from two distinct terroirs roughly 4 km from each other. Hierarchical clustering of data peaks suggested that terroir played a large part in the final composition of the grape berry metabolome (Tarr et al., 2013).

Metabolomics seek to identify the chemical fingerprint of a particular cell, organ, organism or tissue-type that result from and are thus indicative of the chemical processes that occur within the specimen of analysis (Tarr et al., 2013). Using metabolite and gene transcript profiling, Castellarin et al. (2007) highlighted the biosynthesis pathway of flavonols with relationships to water deficit and nitrogen nutrition. The first reaction involves the deamination of phenylalanine by the enzyme phenylalanine ammonia lyase (PAL), into cinnamic acid, thus diverting phenylalanine from the pathway that relates carbohydrates to the synthesis of proteins. Metabolomic studies have also been conducted through ^{1}H NMR spectroscopy which revealed that grapes grown in regions with high sun exposure and low rainfall showed higher levels of sugar, proline, Na, and Ca together with lower levels of malate, citrate, alanine, threonine, and trigonelline than those grown in regions with relatively low sun exposure and high rainfall (Son et al, 2009). The sensitivity of this method has allowed it to be successfully applied to classify wines according to their phenolic profile and allowed the discrimination between wines from different wineries of the same wine-producing zone and between different vintages for wines of the same variety in Greece (Anastasiadi et al, 2009) and Spain (López-Rituerto et al. 2012).

1.2 Biological fingerprint through molecular and “omics” approaches

Despite the interaction between microbial communities and vine plant may be one of the key factors that influence the plant traits, the role of microbes on terroir and vine traits has been largely ignored (Gilbert et al., 2014). However, the recent development of the so-called "omics" techniques (mainly metagenomics, metabolomics, transcriptomics, proteomics, phenomics) has currently made possible to explore the soil functionality, microbial diversity (microbiome) and vine-associated microorganisms at a deeper detail. In fact, the application of omics techniques to soil may enable to determine rare microbial species and discover new compounds or functions (antibiotic, enzymes, etc) from expression of genes of unknown microbial species (Myrold and Nannipieri, 2014). Thus, the application of omics techniques in soil microbiology, associated to standard techniques for soil science, is promising for understanding the functioning of soil and its effect on terroir. To date few studies have been carried out on such issue.

The interface between roots and soil (rhizosphere) is often considered the key point of interaction between a plant and its environment. Microbes colonizing at the root may migrate through the plant to colonize aerial tissues, either internally (endophytes) or externally (epiphytes) (Compant et al., 2011; Bulgarelli et al., 2013). In addition to soil the exploitation of the commensal microbial flora that coexists with the vine may be one of the key factors that influence the plant traits.

Most studies dealing with biological fingerprint are related to the microbial communities present on the surface of the grape berry, which are known to be very large and change according to the stage of grape development (Barata et al., 2012; Pinto et al., 2014). In fact, the microbiological life of wine starts before reception and fermentation of the grapes at the winery. In particular the yeast population and bacterial and fungal consortia inhabiting grape surfaces could reflect a wine region, as reported in some recent studies (Renouf et al., 2005; Setati et al., 2012; Bokulich et al., 2013). However, determinants of regional wine characteristics have not been identified. Renouf et al. (2007) identified 52 yeast species and 40 bacteria. The majority of the bacterial groups were present in the study, in particular the proteobacteria, which are not commonly described in oenology, while the most common oenological yeast (*S. cerevisiae*, *B. bruxellensis*) and bacteria (*O. oeni*, *P. parvulus*, *G. oxydans*) were detected on grape skins from the first stages of development.

Bokulich et al. (2013) surveyed 273 grape musts from two vintages of Chardonnay, Zinfandel, and Cabernet Sauvignon, demonstrating that the grape surface microbial communities present were significantly different between regions (Fig. 1). The authors also show that the degree of significant differentiation between regions is increased dramatically when they look at the biogeography within a grape variety of a given vintage and allude to "the existence of non-random 'microbial *terroir*' as a determining factor in regional variation among wine grapes". This finding suggests that other factors also play a significant role, including host genotype, phenotype (grape variety), local and inter-annual climate variation (vintage) and soil quality. However the specific role of soil microbes was not determined.

In a recent work Martins and co-workers (2013) observed the interaction between telluric bacterial communities and the epiphytic bacteria present on the different grapevine parts. Yet, the ecological interactions and the role of such organisms are still not clear. Vega-Avila and co-workers (2014) reported how soil management (organic vs. conventional) could affect the structure and the diversity of bacterial communities in the rhizosphere of vines of the variety Syrah, in Argentina. Indeed, most of the available literature reports studies concerning the bacterial structure and plant-associated microbiomes (i.e. Dell'Amico et al., 2008; Gilbert et al., 2014) but the functional diversity of such microbiomes are still largely ignored. The combination of different high-throughput culture-independent methods, such as microarrays, metagenomics and microbiome, might elucidate such aspects. For example, considering soils from two close sites in Central Tuscany cultivated with the same variety Sangiovese, but with contrasting wine quality, and water stress, Mocali et al. (2013) used functional GeoChip microarrays and high-throughput DNA sequencing of rRNA genes to explore both microbial composition and functions. Preliminary results revealed different amounts of Actinobacteria and Proteobacteria among the two sites and an overrepresentation of sulfur-oxidation genes in samples where both the increased level of sulfates and the abundance of Firmicutes such as *Sulfobacillus thermosulfidooxidans* occurred. A further step might be sequencing the entire genomic DNA present in a vineyard soil sample and referred to as the “metagenome”, which could provide a cultivation-independent assessment of the largely unexplored genetic reservoir of soil microbial communities and their functions (Daniel, 2005; Mocali and Benedetti, 2010). The importance of this approach has led to the establishment of “Terragenome”, an international consortium for the exploitation of the soil metagenome (Vogel et al., 2009).While these studies represent an initial examination of these relationship, it is an essential step which may potentially help to revolutionize how sites for agriculture are chosen, or indeed how they could be manipulated by probiotics designed to select suitable bacterial species, which could improve soil quality and, hence, crop productivity. Further research is needed to study the degree to which it could enhance some wine characteristics of given terroirs in sites a priori not suitable for generating such characteristics.

2 Terroir zoning at different scales using geospatial technologies

2.1 General perspectives

Differentiation and mapping of regions of grape/wine quality need comprehensive spatial modelling of climatic, soil, and agronomical properties, including their changes through time (Vaudour, 2002; Costantini and Bucelli, 2014). The construction of such spatial models for demarcating terroir units and predicting their viticultural/wine response is undergoing a methodological revolution as new technologies and analytical methods enable the capture of detailed spatial and temporal variability of grapevines according to functional properties in the soil. Recent developments in the combined use of several geospatial technologies including geographic information systems (GIS), global positioning systems (GPS), remote sensing (RS) and direct measurements in the field (proxy sensing) are likely to open many new areas in the spatial modelling of winegrowing terroirs. A considerable amount of research dealing with terroir zoning (> 120 journal papers, book chapters and books) has been published since 2002 (Fig. 2). Most of the published research has been carried out at the within-field scale in the context of the so-called 'site-specific' or 'precision viticulture' (Bramley, 2004, 2005; Bramley and Hamilton, 2004; Bramley et al., 2011, a,b,c,d,e ; Tisseyre and McBratney, 2008; Roudier et al., 2008; Arnó et al., 2009, 2012; Pedroso et al., 2010) and their median study area covered only 0.12 ha, while between-field studies covering more than 0.11 km² only represented ¼ of the total (Fig. 3). There is therefore a gap to fill considering farm (≤ 0.1 to 1 km²), district (≤ some tens km²) to regional scales (≥ tens to thousands km²). The number of map units tends to increase with the log of study area, however its variation is higher for larger study extents than for within-field studies, jointly with the fact that regional studies focus on larger span of target properties. Twenty or so viticultural, environmental or oenological target properties have been considered over the last decade (Table 1), mainly focusing on grape/canopy characteristics and yield or biomass, and secondarily on soil properties at the within-field scale. Table 2 puts together the main last combination of methods, pros, cons, and references examples to study grape characteristics, canopy/yield/biomass/trunk circumference and/or enological parameters, vineyard identification, vine rows and vineyard characteristics, vineyard soil properties (or management zones or terroir units), soil surface condition, erosion and evapotranspiration.

While most former terroir-studies dating back the 1970s-1990s mainly relied on conventional soil mapping and sparse but very time-consuming soil/vine/grape observations at field sites, new techniques are promising for both capturing the detailed spatial variability of vineyard areas and collecting a large amount of soil/vine/grape data. A number of terroir-related studies of the last decade have relied upon a large amount of yield data collected by means of on-the-go yield sensors mounted on mechanical harvesters, which were made commercially available beginning with the 1999 harvest. Pioneering research by Bramley and Hamilton (2004) and Bramley (2005) not only highlighted the magnitude and extent of spatial variability of yield in some Australian vineyards (of between 4.5 and 7.3 ha), but also emphasized the significant influence of soils in driving yield differences. The need to assess spatial variations in soil properties has driven development and application of direct (so-called ‘proximal’) geophysical sensing, particularly for measuring soil apparent electrical conductivity by means of either electrical resistivity surveys and/or electro-magnetic induction scans (EMI) (Lamb et al., 2005; Morari et al., 2009; Taylor et al., 2009; Trought and Bramley, 2011; Fulton et al., 2011; André et al., 2012; Martini et al., 2013; Andrenelli et al. 2013; Priori et al., 2013; Rossi et al., 2013; Brillante et al., 2014). Moreover, the need to assess spatial variation in grapevine biomass and canopy properties, or to map terroir units or to identify vines, has driven the development, acquisition and processing of remote sensing data. Fig. 4 shows that the development of very high spatial resolution airborne acquisitions for the purpose of characterizing grapevine physiological status has represented about 1/3 of the terroir-related studies over the last decade (Hall et al., 2002, 2003; Dobrowski et al., 2003; Lamb et al., 2004; Zarco-Tejada et al., 2005; Martín et al., 2007; Hall et al., 2008, 2013; Gil-Pérez et al., 2010; Meggio et al., 2010). Most approaches combine several data sources, methods (geostatistical/statistical/image processing/computer vision/mechanistical models) and remote or proxy sensors (Table 2). All approaches use geopositioning devices (not detailed in Table 2) the error positioning requirements of which need to be compatible with the study objectives (i.e. accurate positioning of individual sampled vines) and the spatial resolution of the acquired imagery.

2.2 Remote sensing of terroir

The use of remote sensing data in the context of defining terroir and/or within-field management zones in the last decade has given rise to either straightforward use of spectral indices aimed at characterizing vigour or physiological condition (e.g. Hall et al., 2003; Johnson et al., 2003; Lamb et al., 2004; Zarco-Tejada et al., 2005; Rodriguez-Pérez et al., 2007; Hall and Wilson 2013), grape quality (Martín et al., 2007; Martínez-Casasnovas et al., 2012; Primicerio et al., 2014), or more sophisticated image processing aimed at either mapping terroir units (Pedroso et al., 2010; Vaudour et al., 2010; Urretavizcaya et al., 2013) or identifying vineyards (e.g. Wassenaar et al., 2002; Warner and Steinmaus, 2005; Rabatel et al., 2006, 2008; Delenne et al., 2010) (Tables 1 and 2). Other remote sensing studies have dealt with the incorporation of remote sensing information into the prediction of soil properties and their monitoring in vineyards (Vaudour, 2008; Corbane et al., 2010; Lagacherie et al., 2012), the assessment of soil erosion patterns (Quiquerez et al., 2014; Chevigny et al., 2014) or with the prediction of vineyard evapotranspiration (Galleguillos et al., 2010a, b; Bellvert et al., 2014).

2.2.1 Use of vegetation indices for assessing vine vigour/physiology: the NDVI

Typically, the information retrieved from remote sensing has solely relied on the calculation of the most commonly used normalized difference vegetation index (NDVI) defined by equation (1) (Tucker, 1979) from images acquired at or near veraison.

$$NDVI = \frac{(R_{NIR} - R_R)}{(R_{NIR} + R_R)} \qquad (1)$$

Where R_{NIR}, is reflectance in the near infrared spectral band; R_R, is reflectance in the red spectral band.

A number between -1 and +1, quantifying the relative difference between the near infrared reflectance ‘peak’ of vegetation tissues and the red reflectance ‘trough’ due to chlorophyll/carotenoids pigment absorption, the NDVI is the most widely used indicator of plant canopy vigour and relates to the leaf area index (LAI: the ratio of leaf surface area to ground area), fractional cover, biomass and shaded area (Hall et al., 2002; Johnson, 2003; Johnson et al., 2003; Hall et al., 2003; Dobrowski et al., 2008), grape quality (Fiorillo et al., 2012). In Very High Spatial Resolution (VHSR) vineyard imagery, canopy-only pixels tend to have very high NDVI values, commonly ranging between 0.75 and 0.85 (Hall et al., 2002, 2003, 2008). Interpretation of NDVI threshold values requires adaptation to each case study region. This is because typical multispectral images with coarser resolution, like 4 m-IKONOS, may have values that integrate mixed signals from both vine row and inter-row, either bare soil or vegetated with an inter-row crop. However, many studies do not give sufficient detail on the retrieval of NDVI, which basically requires that the digital numbers of the raw images be atmospherically corrected into surface reflectance values prior to NDVI computation, in order to minimize differences in illumination conditions (Vaudour et al., 2014b). In an attempt to address the issue of variable environmental conditions when acquiring multi-temporal imagery, the digital numbers are either normalized (e.g. Vaudour et al., 2010) or alternatively sliced into high, medium and low values for each image (e.g., Dobrowski et al., 2003). However, more often than not the relationships between NDVI and grapevine vegetation/terroir parameters are assessed on an individual image basis, using raw digital numbers (e.g., Johnson et al., 2003; Lamb et al., 2004) or even ignoring atmospheric effects. Using airborne hyperspectral sensors, such as the Compact Airborne Spectrographic Imager (CASI), the Reflective Optics Imaging Spectrometer (ROSIS) and the Digital Airborne Imaging Spectrometer (DAIS-7915) and atmospherically corrected images, Zarco-Tejada et al. (2005) demonstrated that narrow band hyperspectral indices in the 700-750 nm spectral region performed better than NDVI for the purpose of estimating chlorophyll content of leaves, and then detecting iron deficiency chlorosis. Using the Airborne Hyperspectral Scanner (AHS) at a 1000 m-altitude flight enabling a spatial resolution of 2.5 m, Meggio et al. (2010) elaborated other physiological indices for predicting carotenoid and anthocyanin leaf contents, which were related to grape quality in a previous study (Martín et al. 2007).

2.2.2 Identification and/or characterization of vineyards

Some researchers have developed change detection classifications in order to extract regional land use changes including vineyards from multidate, multispectral images with medium spatial resolution such as 30 m-Landsat (Lanjeri et al., 2004; Rodriguez-Pérez et al., 2007; Manandhar et al., 2010). However, much of the work in this area over the last decade is especially marked by the advent of VHSR images, which have favoured innovative approaches for retrieving specific patterns of vineyard arrangements from helicopter colour images with ~0.25 m resolution (Wassenaar et al., 2002), airborne multispectral images with ~2 m-resolution (Gong et al., 2003) or 0.5 m-resolution (Rabatel et al., 2006), satellite panchromatic 1 m-IKONOS images (Warner and Steinmaus, 2005), satellite panchromatic 0.6m-Quickbird images (Rabatel et al., 2006), and ultra-light motorized (ULM) colour 0.5 m-images (Rabatel et al., 2008; Delenne et al., 2010). Approaches for vineyard identification include grapevine field detection (Wassenaar et al., 2002; Rabatel et al., 2006), grapevine field delineation (Da Costa et al., 2007), grapevine row extraction (Hall et al., 2003; Delenne et al., 2010; Matthews and Jensen, 2013; Puletti et al., 2014), and detection of missing plants (Chanussot et al., 2005; Delenne et al., 2010). These approaches have mostly used grey-level images (often the red band) and either relied on frequency analysis (Wassenaar et al., 2002; Rabatel et al., 2006; Delenne et al., 2010) or developed textural analysis, a branch of image processing focused on the spatial statistics of the grey levels of images, the variations of which are perceived as homogeneous areas by the human eye (Haralick et al., 1973). The textural analysis is based on co-occurrences matrices, i.e. "the histogram, in a given neighbourhood for each pixel (e.g 7×7), of the grey-level transitions when considering a given translation in a given direction, from which various parameters can be computed"; for instance energy, correlation, directivity, entropy, and contrast (Rabatel et al., 2006). Provided that the boundaries of each field are available, one can apply a local Fourier transform to extract information on the type of vineyard planting as well as crop spacing and orientation (Wassenaar et al., 2002) or isolate each individual field by selecting the corresponding frequencies in the Fourier spectrum using a specific Gabor filter applied recursively (Rabatel et al., 2008; Delenne et al., 2010). Another approach is that of spatial autocorrelation, requiring that grapevines be equally spaced and that the spatial resolution be fine enough that individual grapevines are discriminated (Warner and Steinbaus, 2005).

2.2.3 Characterization of soil types, soil properties, soil surface condition, erosion

As vineyard inter-rows are frequently left bare, particularly in Mediterranean regions, remote sensing satellite images acquired in Spring, before budburst, have been used for the purpose of mapping soil surface type and condition. For instance, high resolution multispectral 20 m-SPOT images during Spring have been processed using supervised Bayesian maximum likelihood classifier to map red Mediterranean soils originating from Plio-Pleistocene fluvial deposits in the Southern Rhone Valley, with an overall accuracy of 60-70% (Vaudour, 2008). Being important factors in runoff and infiltration processes, soil surface characteristics (SSC) have been mapped at the within-field scale using VHSR images with 0.1 m-resolution acquired by means of Unmanned Aerial Vehicles (UAVs) equipped with a colour camera: Pixy® (Corbane et al., 2008a, b) or DRELIO® (Quiquerez et al., 2014). Depending on SSC classes and surface conditions, overall accuracy ranged from 63 to 84% (Corbane et al., 2008b). Clay content of viticultural soils of the La Peyne catchment in Languedoc (Southern

Mediterranean France) has been successfully estimated from the 2206 nm wavelength of an airborne hyperspectral HYMAP image with 5 m spatial resolution, then spatially predicted from a co-kriging model using this image as co-variable (Lagacherie et al. 2012).

2.2.4 Incorporation of remote sensing information into the spatial modelling of terroirs

Remote sensing images have been used for the purpose of mapping terroir units at regional scales, facilitating selection of plant material, the assemblage of harvest and the monitoring of vine phenology and status across a number of individual fields spread over a regional viticultural area. A terroir concept adapted to spatial modelling from remote sensing considers soil landscape units as base elements for defining terroir units, jointly with climate series and grape composition series (Vaudour, 2003). A soil landscape, also referred to as soilscape (Hole, 1978) or ‘pédopaysage’ (Girard, 1983), can be defined as a landscape unit including a limited number of soil classes that are geographically distributed according to an identifiable pattern (Lagacherie et al., 2001). Soil landscape units were also defined as “a set of pedological horizons and landscape features (vegetation, effects of human activities, geomorphology, hydrology, and parent material) whose spatial organisation allows for defining a soil mantle (or a subset of it)” (Girard, 1983; Carré and Girard, 2002). Their identifiable pattern can be retrieved from visual interpretation of several geographical data layers including image classification results and stereoscopic photograph examination (Vaudour et al., 1998; Vaudour, 2003). The visual interpretation process follows a set of rules describing a conceptual model of soil landscape organization, which relies on the assumption that soil landscape units may be inferred from the geomorphological identification of surficial formations (e.g., mainly glacio-fluvial terraces, in the Rhone Valley), the age and relative elevation of which correspond to distinct durations of pedogenesis (“fersiallitization”) and thus distinct soil layer depths and properties, including soil surface stoniness and colour (Vaudour, 2008). In this pioneering approach, visual interpretation was digitally performed within a GIS along with description and recording of several soil landscape attributes at each delineated polygon area. Potential terroir units were then obtained from the Ward’s clustering of these soil landscape attributes and were further validated against a considerable set of grape composition data over 17 years. In an attempt to reduce the time-consuming stage of visual interpretation, alternate approaches which solely relied on automatic processing of remote sensing and/or morphometric data were proposed, either based on combining per-pixel plus textural classifier (Vaudour, 2003) or on bootstrapped regression trees (Vaudour et al., 2010). In these studies, the resulting map units were termed “terroir” and “viticultural” because they were tested against a considerable set of grape composition data over a long-term period (Vaudour et al., 1998; Vaudour, 2003), or relied on ~50 reference vineyards, the oenological properties of which were known from previous research (Vaudour et al., 2010). In another study, the spatial units of which were termed “terrons”, because they were not tested again viticultural data (Hughes et al., 2012; Malone et al., 2014), Landsat bands and several Landsat band ratios including NDVI have been included as covariates of soil profile data in a number of geostatistical models in order to spatially predict several soil properties. These properties include soil pH, clay percentage, soil mineralogy (clay types and presence of iron oxides), continuous soil classes, and presence or absence of marl: the predicted soil properties were then combined with landscape attributes (derived from a digital elevation model) through fuzzy k-means in order to predict 10 non-marl “terron units” and 2 marl “terron units” depending on the presence of marl (i.e., active lime) at 0.5 m depth. Such an approach of defining “terrons” was initially proposed by Carré and McBratney (2005) and is meant as an initial stage prior to defining viticultural terroirs. A similar study using the term “natural terroir units” and derived from the geostatistical methods described by Castrignanò et al. (2009) was carried out in Tuscany, but did not include remote sensing layers (Priori et al., 2014). “Natural terroir units” (NTU) were first proposed by Laville (1990), as “a volume of the Earth’s biosphere that is characterized by a stable configuration and values of the environmental factors”, and built from morphometric data and lithological units.

Because of the data availability, topography, climate, substrate, and soil are the most commonly used land features in digital terroir zoning (e.g., Carey et al., 2008; Herrera-Nuñez et al., 2011). Actually, there is a conceptual similarity, if not filiation, between the NTU as constructed by Priori et al. (2014) (see § 2.3.3), terron units and soil landscape units.

At the within-field scale, “management zones” originating from a set of soil and/or vegetation proxy and remotely-sensed attributes, typically NDVI, were also obtained using either fuzzy k-means (Bramley and Hamilton, 2004; Pedroso et al., 2010; Taylor et al., 2013; Tagarakis et al., 2013; Priori et al., 2013; Urretavizcaya et al., 2013) or Ward’s clustering (Santesteban et al., 2013). Similar clustering approaches have been performed using a multivariate set of spatial layers including apparent electrical conductivity but without remote sensing images (e.g. Martini et al., 2013).

In order to be applicable in an operational manner, management zones need (Bramley and Hamilton, 2004): (i) to provide stable, constant patterns from year to year; (ii) be related to yield; (iii) be manageable; and (iv) be more economically beneficial than conventional uniform management. An objection to using remote sensing images for delineating management zones is that they "provide only a within-season snapshot and may not relate to final crop yield" (Taylor et al., 2007). According to Tisseyre et al. (2007), and later confirmed by Trought and Bramley (2011), "yield or vigour (pruning weight, size of the canopy) maps of the previous years are relevant in designing site-specific management strategies in the year "n+1" and subsequent years" and conversely to produce maps of quality parameters (sugar content, titratable acidity, pH) which present no temporal stability of within-field variability. This is in compliance with the observations made previously at the regional scale, in the terroir units mapped in the Southern Rhone Valley, for which a long-term frequency analysis of Grenache berry composition had highlighted a strong vintage interaction and no temporal stability of berry composition groups (Vaudour, 2003). When acquired over bare soils in Spring, multispectral SPOT images showed a high temporal stability for deriving homogeneous terroir zones (Vaudour, 2008) which matched those obtained from the supervised support vector machine classifier of a single-year within-season SPOT4-Take Five time series acquired from February to June and accounting for vegetation vigour and phenology (Vaudour et al. 2014a). In order to account for the between-terroir variation in grass vegetation across seasons in vineyards with grass intercrops, regional terroir units may be retrieved from multi-temporal multi-seasonal images (Vaudour et al., 2010).

At the within-field scale, while unsupervised clustering algorithms are commonly used for defining viticultural management zones, other methods have been proposed for cereal-growing systems (e.g., Roudier et al. 2008), in order to address the problem of manageability of the mapped zones. These authors emphasized distinction between classification methods, that define classes such as groups of individual pixels presenting similar properties, and segmentation methods, that define regions or the expression of those groups in space and time forming individual patches. They proposed to use a segmentation method stemming from mathematical morphology and applying the watershed algorithm initially proposed by Beucher and Lantuéjoul (1979) then later formalized by Vincent and Soille (1991). They suggested an approach for reducing the over-segmentation of zones, the number of which was selected following Lark's parsimony principle (2001). According to this principle, the most suitable number of clusters is that "after which the vegetation parameter (such as biomass) variance reduction remains more or less constant or declines more slowly" (Roudier et al., 2008). Generally, the number of within-field zones effectively chosen is empirically defined and comprises between 3 and 5 zones and, when illustrated through raster monovariate maps, eventually described through up to 20 map units based on equal-distance or equal-density intervals (Fig. 3). Pedroso et al. (2010) proposed another within-field segmentation approach based on contextual colour and shape criterion performed on a NDVI airborne ADS40 image with 5 m resolution, aiming at optimising variance partitioning of vine circumference data, removing small unmanageable polygons covering less than 0.1 ha.

Zoning based on automatic procedures should also enable to assess prediction error and/or error uncertainty along with predictions. In the approach elaborated by Pedroso et al. (2010), the effectiveness of the management unit delineations was determined from the adjusted R^2 from ANOVA using the management units as the independent variable and grapevine circumference data as dependent variable. Most terroir units/management zones are validated following a similar variance testing procedure, i.e. demonstrating how well does delineation explain a key growth or grape/berry composition parameter (e.g. Priori et al., 2013; Santesteban et al., 2013). However, while the agronomical/soil property model is verified and/or validated, its spatial prediction error is not or seldom assessed except for geostatistical approaches (Castrignanò et al., 2009; Lagacherie et al., 2012) and for the bootstrapped approach by Vaudour et al. (2010).

2.2.5 Prediction of evapotranspiration and management of irrigation from remote sensing information

Recent developments of remote sensing applications to terroir-related studies have dealt with the prediction of evapotranspiration using multispectral ASTER images through the thermal infrared bands with 90 m resolution (Galleguillos et al., 2011a, b). Using the approach developed by Galleguillos et al. (2011a, b) and a linear downscaling based on land use at smaller pixel sizes, Taylor et al. (2013) demonstrated that the ASTER-derived evapotranspiration-based covariates were of particular significance in the soil depth modelling while water table depth was better explained by models that used digital terrain attributes at smaller pixel size.

2.2.6 Contribution of LiDAR and UAV remote sensing

The use of UAVs in precision viticulture is very recent and promising, as the time of acquisition is tightly controlled and adapted to the user's needs. In particular, promising approaches for mapping vine water stress were presented by Baluja et al. (2012a) and by Bellvert et al. (2014), based on 0.3 m-thermal UAV images acquired around noon (solar time), the pixels of which were significantly linked to midday water potential (MWP) measurements. UAV equipped with LiDAR sensors also enabled detection of rows, the 3D-reconstruction of a vine plantation (Llorens et al., 2011) and the quantifying of vineyard canopy (Llorens et al., 2011; Matthews and Jensen, 2012), while airborne LiDAR images enabled the mapping of landscape linear features (ditches) in a viticultural catchment (Bailly et al., 2008, 2011) and also the hydro-geomorphological analysis of terraced vineyards (Tarolli et al., 2015). UAVs equipped with a visible camera and taking multiangular images using the computer vision technique of structure from motion also enabled the 3D-reconstruction of a vine plantation and were promising in LAI estimation (Matthews and Jensen, 2013).

UAVs allow for acquiring spectral or thermal measurements that are very comparable to proxy measurements and generally carried out along with field proxy measurements. Their use, however, requires a perfect mastering of a chain of image series acquisition, acute georeferencing, spectral calibration, mosaicking and processing, which is the subject of ongoing technical developments, as shown by Verger et al. (2014) for predicting the green area index of annual crops.

2.3 Proxy measurements of terroir and their statistical processing

2.3.1 Geophysical proxy measurements

Observations should account for the entire depth of the root-systems of vines, which may explore the soil parental material, often being surficial formation (Vaudour, 2002, 2003). Geophysical techniques applied to soil (Samouëlian et al., 2005; Doolittle and Brevik, 2014) offer a unique opportunity to explore deep horizons and it may be expected that key soil properties related to soil-vine water balance be retrieved from EMI or ground penetrating radar (GPR) measurements, in possible conjunction with remote sensing images. However, as well as for remote sensing images, these techniques require a local calibration as the measured signal is a bulk signal. Sensing results are often limited to qualitative information and geophysical sensing results are ambiguous, making reliable quantification of sensing information still a major challenge (Werban et al., 2013).

Indeed, geophysical surveys have mainly resulted in delineating within-field zones (Lamb et al., 2005; Taylor et al., 2009; Costantini et al., 2010; André et al., 2012; Martini et al., 2013; Priori et al., 2013), rather than predicting soil properties, such as clay content (Rodríguez-Pérez et al., 2011; Andrenelli et al., 2013), extractable Na^+ and Mg^{2+} contents (Rodríguez-Pérez et al., 2011) or soil moisture (Brillante et al., 2014). Apparent electrical conductivity (ECa) values are “affected by various soil properties in a complex manner and it is difficult to discriminate the weight that each soil parameter has on the final apparent measured ECa” (Martini et al., 2013), so that the Pearson’s correlation coefficient is often not significantly high between ECa and soil parameters such as clay content or gravimetric water content. However, when soil characteristics are available, Brillante et al. (2014) state that it is possible to take them into account into a multiple adaptive regression spline model to build a pedotransfer function for predicting soil moisture from ECa with reduced error (±2% vol.).

2.3.2 Canopy and grape proxy measurements

In addition to field reflectance measurements on leaves to define spectral indices of water status (e.g. Rodríguez-Pérez et al., 2007), several field sensors have been developed in the last decade not only for characterizing canopy and vigour, for instance Crop circle® passive reflectance sensors and active sensors (e.g. Stamatiadis et al., 2010), Greenseeker® reflectance sensor computing NDVI values in real time (e.g. Mazetto et al, 2010), but also for measuring grape quality parameters including using the Multiplex® portable sensor (Ben Ghozlen et al., 2010; Bramley et al., 2011b; Baluja et al., 2012; Agati et al., 2013). In particular, both fluorescence based anthocyanin and flavonol indices originating from this sensor showed high potential for monitoring technological maturity according to the recent findings by Agati et al. (2013), on Sangiovese and Vermentino varieties respectively.

2.3.3 The issue of big data handling and the statistical processing of the varied spatial data collected

In addition to remote and proxy data collected from distinct sensors, the use of mobile devices with multitag technologies (Cunha et al., 2010; Luvisi et al., 2011) facilitates the recording of a great wealth of data. These numerous spatial data have stimulated new developments in both software and hardware, jointly with statistical processing stemming from geostatistics, image pattern recognition, satellite image processing, which includes machine learning. However the most common pattern adopted for within-field spatial data and observed for ~40 of the last-decade terroir-related research (Table 3) relied on geostatistical analysis, as emphasised by Baveye and Laba (2014). Considering the target parameter as a random property following a random process with assumption of stationarity (i.e. there is the same degree of variation from place to place), Matheron (1962, 1965) formalized the approach to predict target properties from spatially correlated sample data through the computation of the semi-empirical variogram, to which are fitted a number of standard parametric models (Oliver and Webster, 2014). “Kriging is a generic term for a range of least-squares methods to provide the best linear unbiased predictions in the sense of minimum variance”, through solving a set of linear equations (the kriging system) from the fitted variogram function and the available data (Oliver and Webster, 2014). Ordinary kriging based on primary spatial information such as yield or ECa is the most popular method used in terroir-related studies (Table 3), though more sophisticated spatial models using ancillary spatial information have also been built, such as block co-kriging with an hyperspectral image (Lagacherie et al., 2012) or factorial kriging of several soil variables and ECa (Morari et al., 2009). To single out NTU-based viticultural terroir units at the province scale (1:125,000 scale), Priori et al. (2014) combined a multivariate and geostatistical approach showing the variability of the soilscapes within the DOC and DOCG territories in Italy. A first Principal Component Analyses (PCA) was performed to relate climate, pedoclimate and morphometric features with the viticultural data, and a second PCA linked the main soil features with viticultural data. The two PCAs revealed which environmental features were better related to the viticultural parameters of the experimental farms. Several geostatistical models (Castrignanò et al., 2009) were then used to spatialize the selected environmental features: (i) regression kriging to interpolate rooting depth; (ii) simple kriging with varying local means, to interpolate coarse fragments and redoximorphic mottles depth; and (iii) multicollocated simple cokriging with varying local mean to interpolate AWC, clay and sand content. Finally, a k-means cluster analysis was performed in the viticultural areas, using the selected variable maps (mean annual temperature, mean annual precipitation, mean annual soil temperature, elevation, clay, sand, coarse fragment content, available water capacity, rooting and redoximorphic mottles depths) to determine the NTU-based viticultural terroir units.

The map results obtained from digital terroir zoning performed at regional scales over some thousands of km² lead needing to better understand the issue of the relevant scales for defining and managing terroirs. It is important to both address the usefulness of both spatial and temporal resolutions that provide insights in terroir zoning according to the aim of the research or management practice. Studies need to examine the nature of within-field zones and the regional terroir units as the relationship between the number of map units and the surveyed area is log-linear (Fig. 5).

The underlying motivations for detailed assessments of the within-field spatial variation of yield/biomass/soil properties are related to the variable-rate application of inputs and selective harvesting at parcel level (Arnó et al. 2012). However considering the within-field scale only may be questionable in the case of highly-parcelled vineyards of less than 1 ha each such as in European countries with secular viticulture. More than ever, the issue of information synthesis and spatial scale is at the very heart of the spatial modelling of terroir (Vaudour, 2002). Considering a whole 90 ha-vineyard composed of 27 contiguous fields, Santesteban et al. (2013) showed that a per-field, within-field study would have resulted in missing the spatial trend due to slope. Therefore the usefulness of the multiple-field approach becomes one of a “whole-vineyard” or regional approach. Such issues similarly arise when attempting to predict the vine water status from a set of leaf/stem predawn water potential (PLWP/SWP) or midday (MWP) measurements, which are very time-consuming, require accurate methods to collect with a pressure chamber (Scholander et al. 1965), and should be made at several fields managed by the vineyard operation. Using PLWP (Acevedo-Opazo et al., 2008a,b, 2010b) or MWP (Acevedo-Opazo et al., 2010a, 2013) measurements, Acevedo-Opazo et al. (2008a, b, 2010a, b, 2013) elaborated a linear model applicable at the within-field level but requiring a time-consuming calibration set; in the case of PLWP, it corresponded to rainfed vineyards with high water stress, while in the case of MWP, it was aimed at scheduling irrigation. A similar approach using $\delta^{13}C$ measurements as ancillary variables enabled extrapolation of stem water potentials for a rainfed vineyard with moderate water stress (Herrero-Langreo et al., 2013). These approaches may be transferable to a whole-vineyard scale (~29 km²), according to Baralon et al. (2012), who constructed an important measurement database (58 fields monitored in all) over the course of three consecutive vintages. This approach considered a stratified sampling based on soil types, which is most effective when water restriction is high (Taylor et al., 2010). However, several limitations hinder its practical application, namely those due to spatial sampling optimization and improvement of the temporal resolution of the model, using real-time monitoring sensors (such as sap flow sensors) (Herrero-Langreo et al., 2013). According to farmers, a model should be capable of predicting water stress at least two weeks before severe irreversible water stress damage occurs (Viaud, personal communication, 2014).

Arnó et al. (2012) stated that overall within-field variability of grape yield and quality raises important questions concerning whether site-specific crop management could be used in vineyards. Problems arise, in particular, when looking for causes of this variability, especially those related to the presence of soil carbonates which may lead to Mn deficiencies, with deleterious effects on grape colour. Another problem pointed out by Baveye and Laba (2014) related to N or P manuring is the frequent possibility that P or N deficiency in a management zone may be due to a higher leaching rate in the area, leading to an increased rather than decreased risk of groundwater contamination if more fertilizer is applied in this management zone.

2.4 Modelling and depicting climate at the region to vineyard scale

Another growth area in terroir zoning studies is the development of spatial climate data products. Historically, a region’s climate and suitability for viticulture were assessed via climate station analyses, which seldom depict the spatial variation of climate in actual or prospective vineyard sites within wine-producing regions (Jones et al. 2010). As a result, reference vineyard networks were developed within regions to better capture the spatial climate characteristics (e.g., Jones and Davis 2000). However, the low network density even in reference vineyard networks does not account for the range in mesoclimates found within regions. To overcome these issues, spatial climate data products providing robust, validated, and more spatially appropriate climate data have been developed through the interpolation of existing long-term, quality-controlled data sources. Numerous techniques such as kriging and smoothing splines have been used to produce interpolated surfaces from hundreds to thousands of stations containing valuable meteorological inputs. The results are spatial climate products at daily or monthly time scales and at a range of spatial and temporal scales such as Daymet (Thornton et al. 1997), PRISM (parameter-elevation relationships on independent slopes model) (Daly et al. 2008), and WorldClim (Hijmans et al. 2005). Most of these approaches use elevation data (digital elevation data) and station climate data to calculate a climate-elevation regression for each grid cell, and stations entering the regression are assigned weights based primarily on the physiographic similarity of the station to the grid cell (Daly et al. 2008). These models attempt to account for location, elevation, coastal proximity, aspect, vertical differences in atmospheric layers, and orographic effects; although they can vary in the number and complexity of the factors involved. Validation procedures have shown that these products are generally robust at the scales for which they have been developed (Daly et al. 2008) and even at sub-grid resolutions, showing accuracy in regions characterized by sparse station data coverage, large elevation gradients, rain shadows, inversions, cold air drainage, and coastal effects.

Using these new gridded climate data sets, previous studies have examined viticulture region climate characteristics at various resolutions including 18 wine regions in Europe (1 KM; Jones et al. 2009), 50 PDOs and sub-PDOs in Portugal (1 KM; Jones and Alves 2012), 35 PGIs and PDOs in Greece (1 KM; Anderson et al. 2014), 135 American Viticultural Areas in the western United States (400 m; Jones et al. 2010), 63 Geographical Indications in Australia (500 m; Hall and Jones, 2010), and 21 wine regions in New Zealand (500 m; Anderson et al. 2012) providing more holistic measures to help understand the range of climates within viticulture regions. Various climate parameters such as heat accumulation indices, frost timing, evapotranspiration, and dryness indices are often used along with mapping and spatial summaries over delimited winegrowing regions, ultimately helping to define the climate component of terroir over time and space.

Much work has been done examining the likely impacts of climate change on water and/or nitrogen dynamics through models such as Lebons's (adapted from Riou's models, 1989, 1994, Lebon et al., 2003) Lin and Host's (Costantini et al., 2009), SWAT (Martínez-Casasnovas et al., 2013; Ramos and Martínez-Casasnovas, 2014), and SWAP (Bonfante et al., 2011) hydropedological models that aim to simulate the dynamics in seasonal soil water balance. Kersebaum's model was proposed to simulate nitrogen dynamics (Nendel and Kersebaum, 2004), while the STICS model simulates crop growth, soil water and nitrogen balances driven by daily climatic data (Brisson et al., 2009), the WaLIS model simulates water partitioning in intercropped vineyards (Celette et al. 2010). WaLIS was also used to quantify the effects of water deficit and nitrogen stress on yield components (Guilpart et al., 2014). To model the seasonal pattern of evaporation from a grassed Mediterranean vineyard, Montes et al. (2014) recently elaborated a Soil-Vegetation-Atmosphere-Transfer (SVAT) model coupling an evaporation formulation together with a reservoir-type soil water balance model. Attempts have also been made to use micromorphology to characterize and monitor soil internal drainage of vineyards and olive tree groves (Costantini et al., 2006). Bonfante et al. (2011) have integrated the outputs of the SWAP model with a set of regional spatial data in order to map crop water stress indices together with soil map units, bioclimatic indices, and potential radiation onto terroirs with simulated crop water status. However, scale issues need to be further addressed for both terroir zoning and other applications such as the mapping of water stress. In vineyards, micro-variations in weather and climate often produce the greatest risk (e.g., frost or freeze zones, heat stress areas, etc.) and to truly address climate change we will need finer scales to assess the potential impacts (Quénol and Bonnardot, 2014).

3 Perspectives: terroir sustainability assessment and the design of new preservation practices

The above-mentioned modelling approaches of terroir or terroir components with the perspective of both spatially and temporally updating information lead to considerations in an emerging and complex study area: the sustainability assessment of terroirs. Some recent zoning studies using geospatial technologies have addressed this issue, in terms of erosion, (Table 2). Terroir sustainability started to be accounted for in the late 1990s, through some growers unions' initiatives in both California and Champagne, and also through the growing awareness of the soil contamination by copper due to the cumulated use of Bordeaux mixture (Vaudour, 2003). Mediterranean viticultural areas are amongst those most exposed and aware of the sustainability issue, because of the soil losses due to intense erosional processes (e.g. Le Bissonnais et al., 2007; Martínez-Casasnovas et al., 2009, 2013; Novara et al., 2011), which may lead to the destruction of a vineyard field (Fig. 6). Another issue is that of abandonment and land use change due to either urban pressure, aging of farmers or declines in profitability (Fig. 7).

Depletion of soil fertility in general, along with the concomitant problems of weeds, pests and diseases, is the fundamental root cause of low agricultural production at the global level (Tan et al., 2005). Even if grapevines are not nutrient demanding, it nevertheless requires an adequate supply, which may no longer be the case in terroirs where the soils are undergoing degradation processes, especially including soil losses (Le Bissonnais et al., 2007; Martínez-Casasnovas et al., 2009, 2013; Paroissien et al., 2010; Novara et al., 2011; Quiquerez et al., 2014; Chevigny et al., 2014; Lieskovsky and Kenderessy, 2014), nutrient depletion (Ramos et al., 2006), compaction (Lagacherie et al., 2006), salinization/sodization (Clark et al., 2002; Crescimanno and Garofalo, 2006; Crescimanno et al., 2007; Costantini and Lorenzetti, 2013), pesticide runoff and deposition (Landry et al., 2005; Louchart and Voltz, 2007; Lacas et al., 2012; Daouk et al., 2013; Lefrancq et al., 2013), and copper contamination (Pieztrak and McPhail, 2004; Chopin et al., 2008; Wightwick et al., 2008; Mirlean et al., 2007, 2009; Rusjan et al., 2007; El Hadri et al., 2012; Fernández-Calviño et al., 2013; El Azzi et al., 2013). In Burgundy, using vine-stock unearthing–burying measurements (Brenot et al., 2008), Chevigny et al. (2014) estimated that the erosion rate had increased significantly over the last decade, and also that spatial distribution of erosion had changed and was now basically controlled by slope steepness and present-day vineyard chemical weeding and no tillage management instead of past surface tillage. Using the same method in Languedoc, Paroissien et al. (2010) estimated that the average soil loss reached 10.5 t $ha^{-1}year^{-1}$ and was much higher than the average erosion rates established around 3 t $ha^{-1}year^{-1}$ for the other cultivated soils. The high vulnerability of vineyard soil to erosion may be partly explained by the steep slopes where vineyards are established, but also by the generally low content in organic matter (<2%) and the low microbial activity of soils, which leads to a reduced aggregate stability that increases soil crusting and soil erosion (Le Bissonnais et al., 2007). Very poor eroded soils can show low or very low nitrogen content, as a consequence of low soil organic matter. In the Pénédes viticultural region, Ramos et al. (2006) estimated that runoff processes exported significant amounts of nutrients, which represented as much as 8 kg ha-1 year-1 of N and 6.5 kg ha-1 year-1 of P. Moreover, the nitrogen deficiency can be enhanced in moderate to severe water stress conditions (Costantini et al., 2013). According to Blavet et al. (2009), chemically weeded vineyards result in the highest runoff rates and soil losses, but the losses can be reduced when the prunings are left on the soil, when straw mulching is used, when rock fragments are left, and when grass intercrops are used. The corollary issue of runoff is that, in addition to soil erosion and soil nutrient loss, it also leads to fertilizer and pesticide residue loss to surface waters, depending on the timing of the applied pesticide (Louchart and Voltz, 2007).

In order to mitigate environmental damages and foster soil conservation and restoration, studies over the past decade have focused on the specific effect of one or several soil surface management techniques, such as cover cropping vs chemical weeding or tillage and/or mulching, on soil structural stability (Goulet et al., 2004, Ruiz-Colmenero et al., 2011, 2013), soil loss (Ruiz-Colmenero et al., 2011, 2013; Novara et al., 2011; Lieskovsky and Kenderessy, 2014), pesticide leaching (Landry et al., 2005), soil nutrient and water management and vine growth and yield (Steenwerth and Belina, 2008, 2010; Ripoche et al., 2010, 2011; Novara et al., 2013), soil C dynamics (Steenwerth et al., 2010; Agnelli et al., 2014), and grape quality (Lee and Steenwerth, 2013). As recently described by Ruiz-Colmenero et al. (2013) and Agnelli et al. (2014), a greater organic matter accumulation is fostered by the presence of the grass cover and the absence of tillage. In the Vosne-Romanée area in Burgundy, Landry et al. (2005) showed that glyphosate and its metabolite (AMPA) leached in greater amounts through a chemically treated bare Calcosol than through a vegetated Calcosol. In an upslope vineyard in the Beaujolais area, Lacas et al. (2012) demonstrated the usefulness of a grass buffer strip on a coarsely textured soil to limit the dispersal of diuron losses by runoff towards surface and subsurface water. Jacobson et al. (2005) studied the leaching of the herbicide diuron jointly with that of copper, through vineyard soils contaminated with copper, and found no direct interaction between the metal and herbicide, but interpreted that Cu was possibly affecting microbial activity, resulting in slight increases in diuron persistence.

Despite the varied environmental problems that viticultural terroirs are facing currently, putting their functioning at risk, the design of new preservation and mitigation practices has just begun to be addressed in the literature of the past decade. If some methods to globally assess the sustainability of agricultural systems have emerged (Bockstaller et al., 2009), they have seldom addressed that of viticultural system (Abbona et al. 2007) and not only below the environmental point of view, but also for the attractiveness of the landscape, that in many viticultural areas conveys a remarkable added value to the wine produced and the region (Tempesta et al., 2010; Costantini and Barbetti, 2008).

The global water crisis, particularly water scarcity (Hanjra and Qureshi, 2010), that threatens those viticultural areas under semi-arid or arid climates, particularly in the Mediterranean area

(Iglesias et al., 2007; Plan Bleu, 2013), questions the relevancy of irrigating, in addition to the degradation effects that this practise may have on soil properties over a long-term period and its high remediation costs (Hajkowitcz and Young, 2005). To address the issue of terroir sustainability in the years to come, one of the greatest challenges is the design of efficient soil restoration practices along with crop and/or intercrop management plans, taking into account the possible effects of climate change. This implies a complex multicriteria decision analysis, as attempted by Ripoche et al. (2010) in order to evaluate a range of intercrop management plans. The monitoring of soil quality as potentially obtainable from remote/proxy techniques is likely to identify when soil degradation is occurring in order to allow management intervention. Amongst the key biological indicators are soil organic carbon, potentially mineralisable nitrogen and microbial biomass (Riches et al., 2013, Salome et al., 2014, Zornoza et al., 2015), although further research is still needed to identify a suite of biological indicators for viticultural soils. Application of organic amendments is likely to improve soil quality but its effects are seldom studied, particularly over long-term experiments (Tatti et al., 2012). In rainfed Marchesi Antinori vineyards observed over two consecutive growing seasons, Baronti et al. (2014) suggested that biochar amendment could be used to improve soil water content, but other possible negative effects of changes in surface albedo or accumulation of polycyclic aromatic hydrocarbons still need to be studied. In contrast, considering a 3-year period in a Valais vineyard (Switzerland), Schmidt et al. (2014) observed only small and mostly-non-significant effects of either biochar or biochar-compost amendments. However, over the same duration in a vineyard in Jumilla (Spain), other organic inputs such as winery and distillery waste composts induced “an increase in the activity of the soil microorganisms and in the soil macro and micronutrient contents, as well as a slow release of inorganic N” (Bustamante et al., 2011), in a soil characterized by a highly calcareous sandy-loam soil (Torriorthent). When soils are biologically very poor, even organic farming may be not enough to restore soil functionality, at least over a short-time period (Costantini et al., 2014). Coll et al. (2011) evaluated the long-term effect of organic viticulture on soil quality in commercial vineyards of Languedoc where plots which had been organically managed for 7, 11 and 17 years, comparing them to conventionally managed plots. The results emphasised that a transition period of 7–11 years, depending on the considered indicator, was needed to clearly separate conventional and organic farming. The overall benefits of organic farming were an increase of soil organic matter, potassium content, soil microbial biomass, plant-feeding, fungal feeding, nematode densities, while its drawbacks were increased soil compaction, decreased endogeic earthworm density (due to reduced soil porosity), both consequences of the increase of the traffic for tillage and phytosanitary treatments in organic management. The grapevines studied by these authors were not intercropped with grass, and knowledge is actually scarce about the joint long term environmental effects of the various possible sets of practices, such as cover/intercrop or not, mulching, mouldboard ploughing or/and tillage depth and frequency, type/quantity of applied organic amendments, and the use of chemical fertilizer or not.

Further studies should also address the possible reintroduction of agroforestry systems jointly with vineyards, as traditionally practised in Mediterranean regions, such as in Ancient Greece (Vaudour and Boulay, 2013) or in Italy and Provence till the XIXth century. Those systems are known to limit water consumption, fertilizers and pest diseases, particularly Botrytis cinerea bunch rot in Portugal (Altieri and Nicholls, 2002), and have positive impacts on phytoseid mite species, known for their ability to control mite pests, as shown in the last decade for vines co-planted with *Sorbus domestica L.* or *Pinus pinea L.* in Languedoc (Liguori et al., 2011).

4 Conclusions

Recent studies based either on metabolomics or on the Sr isotopic ratio lead to a strengthening of the assumption that geographical origin does leave a footprint in wines and that both soil and substrate, in interaction with climate and cultural choices, influence the shaping of grapevine phenology and grape and wine quality. Furthermore, the use of the current "omics" technologies seems to confirm the existence of a ‘microbial terroir’ as a key factor in regional variation among wine grapes. Despite the role of soil microbial communities on terroir is still unclear, in the next future the combination of the omics techniques and traditional approaches could give further insights on activity and composition of vine-associated microbes, especially those living on the grape or leaf surface (phyllosphere) and root surfaces (rhizosphere) but also within the plant tissues (endophytes), and their interactions with plant and soil.

Differentiation and mapping of viticultural terroirs meant as homogeneous regions of grape/wine quality need comprehensive spatial modelling of soil, agronomical and climatic properties, including their changes through time. As such the development of a myriad of either remote or proxy sensing techniques and the corollary challenge of processing large quantities of data acquired at a very fine spatial resolution and/or at several spatial resolutions, scales, and organisational levels. These techniques in data collection and processing are needed to produce easy-to-update decision maps with associated uncertainties that allow users to make appropriate and timely management decisions. This is a revolution in the spatial management of terroir units, as the managed zones will be updatable and the effects of viticultural and/or soil management practices might be easier to control. The perspective of facilitated terroir spatial monitoring makes it possible to address another great challenge in the years to come: the issue of terroir sustainability and the construction of efficient strategies for assessing and applying them across numerous scales. These include the design of efficient soil restoration practices along with crop and/or intercrop management plans, and/or agroforestry viticultural systems, that take into account the possible effects of climate change. Therefore, terroirs are more and more likely to be addressed through the concept of ecosystem services, as viticultural agro-ecosystems, the services of which need to be constantly evaluated and rationalized.

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Table 1. Target variables of the zoning studies carried out over the 2002-2013 period (see Fig. 2).

viticultural	**N**	**environmental**	**N**	**oenological**	**N**
canopy characteristics	20	soil properties	14	grape composition	24
yield	17	soil units	6	wine composition	3
biomass	15	soil surface condition	3	wine sensory attributes	3
vine water status	12	temperatures	3		
vineyard identification	11	erosion	3		
management zones	8	climatic zones	2		
terroir units	6	land use changes	2		
pest/weed management	6	artificial drainage network	2		
evapotranspiration	4	landslide	1		
vine rows	4				
vineyard characteristics	3				

Legend: N, number of papers

Table 2. Typology of zoning studies carried out over the 2002-2014 period

Targets	**Scale**	**Data**	**Methods**	**Pros**	**Cons**	**References (e.g.)**
Grape composition	plot	FM	BK then FA followed by Fuzzy KM	Fine-scale	Time-consuming, high sampling density (3 m)	Baluja et al. (2013)
	plot	FM, airborne NDVI	LR	Fine-scale spatially exhaustive data	Specific calibration for each plot	Lamb et al. (2004), Hall and Wilson (2013)
	plot	FM, Fluo and/or airborne NDVI, ChloM	Spectral index, CF	Replaces expensive measurements	Need of specific calibration for each plot?	Ben Ghoslen et al. (2010), Baluja et al. (2012b), Agati et al. (2013)
	district	VIS-NIR HypS airborne imagery, FM	Spectral indices, LR	Fine-scale spatially exhaustive data	Specific calibration for each plot	Martín et al. (2007), Meggio et al. (2010)
	region	FM, VIS-NIR-SWIR HR satellite imagery, TopoP and/or soil map and/or SPE	Multitemporal SC, SA	Large-scale spatially exhaustive data, landscape-scale relevant for unions of winegrowers	Spatial resolution of imagery appropriate if homogeneity of practices	Vaudour (2003), Vaudour et al. (2010, 2014)
Canopy characteristics, yield and grape composition	plot	FM, YM	OK then KM and/or LOGR and/or NPT	Fine-scale	Time-consuming, high sampling density (2 m)	Bramley and Hamilton (2004), 2005 ; Tisseyre et al. (2008); Bramley et al. (2011a), Arno et al. (2012)
	plot	FM (including CC), soil ECa, TopoP	NDVI, Fuzzy KM, correlations	Fine-scale	Need of further validation	Tagarakis et al. (2013)
	plot	FM, VHSR satellite NDVI	Fuzzy KM and/or GK, ANOVA and/or PCA and/or NPT	Early grape composition, definition of harvest zones	Spatial resolution of imagery not quite appropriate ?	Martinez-Casanovas et al. (2012), Urretavizcaya et al. (2013)
	plot	FM, airborne NDVI (0.3 m)	Correlations	Easy-to-use, spatially exhaustive data	Specific calibration for each plot	Hall et al. (2011)
	farm	FM (including $\delta^{13}C$) , airborne NDVI, soil ECa, TopoP	WHC, ANOVA, IDW thresholding	Relevant scale for winery, good compromise data collection/results	Need to test feasibility at the winery scale	Santesteban et al. (2013)
	farm/ district	FM (LAI), VSHR satellite NDVI	LR	Easy-to-use, spatially exhaustive data	Specific calibration for each image, spatial resolution of imagery not adapted to every viticultural system	Johnson et al. (2003)
	district	VIS-NIR HypS airborne imagery, FM (including leaf LabR spectra)	LR, spectral indices, inversion of PROSPECT-rowRCRM model for predicting leaf reflectance	Fine-scale spatially exhaustive data	Complex parameterization	Zarco-Tejada et al. (2005)

	region	FM, soil map, TopoP, daily climatic data	SWAP mechanistic model	Landscape-scale relevant for unions of winegrowers	Needs detailed data at specific sites for parameterization	Bonfante et al. (2011)
Yield, oenological parameters	plot	FM, YM, soil ER, airborne NDVI and/or topographic parameters	OK and/or PCA then KM	Fine-scale, whole soil-vine-wine chain considered	Time-consuming, high sampling density (≤ 2 m), multisensors collection, microvinifications	Bramley et al. (2011c, d), Priori et al. (2013)
Biomass, oenological parameters	plot	FM, airborne NDVI	NDVI thresholding, then LR	Fine-scale	Time-consuming, high sampling density (5 m)	Fiorillo et al. (2012)
Yield, vine trunk circumference	plot	FM, soil ER, TopoP	LR, Fuzzy KM, ANOVA	Fine-scale	Time-consuming data collection	Rossi et al. (2013)
Vine trunk circumference, management zones	farm	FM, airborne NDVI	Spatially constrained KM	Manageable zones	Need of effective testing of the aggregation-component of the algorithm	Pedroso et al. (2010)
Vine water status	plot	FM (including PLWP), airborne NDVI	NDVI thresholding, LCCAOT	Temporal stability of the zoning over 3 years	One soil type considered, specific calibration for each block required	Acevedo-Opazo et al. (2010a)
	plot	FM (including $\delta^{13}C$ and SWP)	LR, NPT, LCCAOT, IDW thresholding	High validation performance	Specific calibration for each block required	Herrero-Langreo et al. (2013)
	plot	FM (PLWP or SWP), VIS-NIR MS and thermal UAV imagery	Spectral indices, LR		Specific calibration for each plot required	Baluja et al. (2012a), Bellvert et al. (2014)
	farm	FM (including PLWP), airborne NDVI, soil ER	NDVI thresholding, PCA, NPT	Temporal stability of the zoning over 3 years	Auxiliary information on soil types needed	Acevedo-Opazo et al. (2008)
	district	FM (PLWP)	LCCAOT, LR	Easy-to-apply for winegrowers	Need of further validation	Baralon et al. (2012)
Vine rows	plot	Airborne NDVI	VineCrawler algorithm	Suited for vineyards with large rows/interrows	Not suited for dense low-vigour vineyards with missing vines	Hall et al. (2003),
Vineyard identification, vine rows, and vineyard characteristics	plot	FM (LAI), VIS multiangular UAV imagery	SfM, multiple regression	Promising ; 3D-reconstruction	Big data ; further improvements needed to improve LAI prediction	Matthews and Jensen (2013)
	district	VIS-NIR MS ULM or airborne imagery	TA, FT and/or « object-classifier »	Easy implementation, high processing speed, limited amount of parameters, export into GIS shapefile format	Further validation needed for detecting missing plants, further use of all spectral information	Rabatel et al. (2008), Delenne et al. (2010), Puletti et al. (2014)

	district	FM, airborne LIDAR	Georeferencing, LR and/or KM, TA	Performing, 3D-reconstruction	Need of further test on complex viticultural landscapes with several training modes? Cost-prohibitive repeated acquisitions	Llorens et al. (2011), Matthews and Jensen (2012)
	region	VIS MS helicopter imagery	FT, TA	Robust recognition of vineyards	Ambiguities in identifying training modes	Wassenaar et al. (2002)
	region	VHSR MS satellite imagery	TA, autocorrelogram pattern	Robust recognition of vineyards	Better adapted to equally spaced vineyards with large rows	Warner and Steinmaus (2005)
	region	MR MS satellite imagery	Multitemporal SC	Fast unexpensive landscape-scale map	Not accurate enough at the farm/plot scales	Lanjeri et al. (2004), Rodriguez-Perez et al. (2008)
Soil properties, potential management zones	plot	Soil ECa and/or ER, FM (soil analysis) and/or airborne/satellite NDVI	FKA, KM	Additional description of residual variation within classes provided	Ground-truth soil samples mandatory to understand + interpret EMI mapping	Morari et al. (2009), André et al. (2012), Andrenelli et al. (2013), Martini et al. (2013), Priori et al. (2013a)
	farm	Soil ECa, soil map	Geostatistical descriptors, FA	Satisfactory discrimination between soil types	Reference soil map needed in addition to ECa	Taylor et al. (2009)
	region	FM (clay content), airborne VIS-NIR-SWIR HypS imagery	CR, coK, BcoK	Spatially validated	Further test on other soil types/cultural practices	Lagacherie et al. (2012)
	region	FM (soil types, analyses), TopoP, geological map, soil map and/or climatic data	GIS combination of raster layers and/or PCA and/or KM	Landscape-scale relevant for unions of winegrowers ;	Need of further spatial validation; potential high number of output map units	Carey et al. (2008), Herrera-Nuñez et al. (2011)
	region	FM (soil types, analyses), TopoP and/or satellite HR imagery	Different geostatistical models, SC, PCA, fuzzy KM	Landscape-scale relevant for unions of winegrowers ; spatially validated	Need of further viticultural characterization + validation	Hugues et al. (2012), Malone et al. (2014), Priori et al. (2014)
Soil surface condition	plot	FM (soil infiltration rate, clod sizes), VIS UAV imagery	SC, multiscale « object-classifier »	Enables to avoid time-consuming field descriptions	Possible improvements considering NIR and SWIR ranges	Corbane et al. (2008)
	region	FM (BRDF), VIS helicopter imagery	TA, BRDF model	Extraction of bare soil inter-rows	Possible improvements considering NIR and SWIR ranges; need of further validation	Wassenaar et al. (2005)

Erosion	plot	FM (SUM), TopoP, historical landuse maps and/or soil ER,and/or VIS UAV imagery	KM, multitemporal SA	Fine-scale spatially exhaustive data	Further developments at a higher scale; time-consuming observations	Brénot et al. (2008), Paroissien et al. (2010), Chevigny et al. (2014), Quiquerez et al. (2014)
	region	FM (SUM), TopoP, historical landuse information	multitemporal SA	Variability of multi-decennial erosion across local and regional scales with acceptable investigation costs	Time-consuming observations	Paroissien et al. (2010)
Evapotranspiration	region	FM (EdCov, soil water), VIS-NIR-SWIR-thermal satellite imagery	HYDRUS-1D model, S-SEBI and WBI models	accuracies between 0.8 mm.d^{-1} and 1.1 mm.d^{-1}compatible with applications	Further need to address model sensitivities , inclusion of row orientation, landscape characterization	Galleguillos et al. (2011a, b)

Legend: BcoK, block co-kriging; BK, Block kriging; CC, crop circle sensor canopy measurements; BRDF, bidirectional reflectance distribution function; CF, curve fitting; ChloM, chlorophyll content measurements on leaves (chlorophyll meter) ; CoK, co-kriging; CR, continuum removal; Eca, apparent electrical conductivity; EdCov, eddy covariance measurements; EMI, electro-magnetic induction; ER, electrical resistivity; FA, factorial analysis; Fluo, fluorescence proxy measurements in the field; FKA, factorial kriging analysis; FM, field measurements at point locations; FT, Fourier Transform; GK, global kriging; GPR, ground penetrating radar; IDW, inverse distance weighting; HR, high spatial resolution; HypS, hyperspectral; KM, k-means clustering of interpolated values; LabR, laboratory reflectance spectra; LAI, leaf area index; LCCAOT, linear coefficient of correlation analysis and covariance analysis between sites over time; LR, linear regression; LOGR, Logistic regression; MR, medium resolution; MS, multispectral; NPT, non-parametric test; OK, ordinary kriging; PCA, Principal Components Analysis; PLWP, predawn leaf water potential; rowRCRM, Markov-Chain Canopy Reflectance Model; SA, spatial analysis; SfM, structure from motion; SPE, stereoscopic photograph examination; SUM, stock unearthing measurement; SWIR, shortwave infrared; SC, supervised image classifiers (such as regression trees, support vector machines, Bayesian Maximum Likelihood); SWAP, soil-water-atmosphere plant model; SWP, stem water potential; TA, textural analysis; TopoP, topographic parameters (mainly elevation, slope and/or topographic wetness index); UAV, Unmanned aerial vehicle; ULM, ultra-light motorized; VHSR, very high spatial resolution; VIS-NIR, visible and near infrared; WHC, Ward’s Hierarchical Clustering; YM, yield maps from grape harvester equipped with yield monitor.

Table 3. Use of geostatistics in the zoning studies carried out over the 2002-2013 period (see Fig. 2).

Use of geostatistics	N
no geostatistics	87
ordinary kriging	15
geostatistics but unexplained	8
block kriging	6
further use of variogram attributes	5
factorial, co-kriging, block co- kriging	2

Legend: N, number of papers

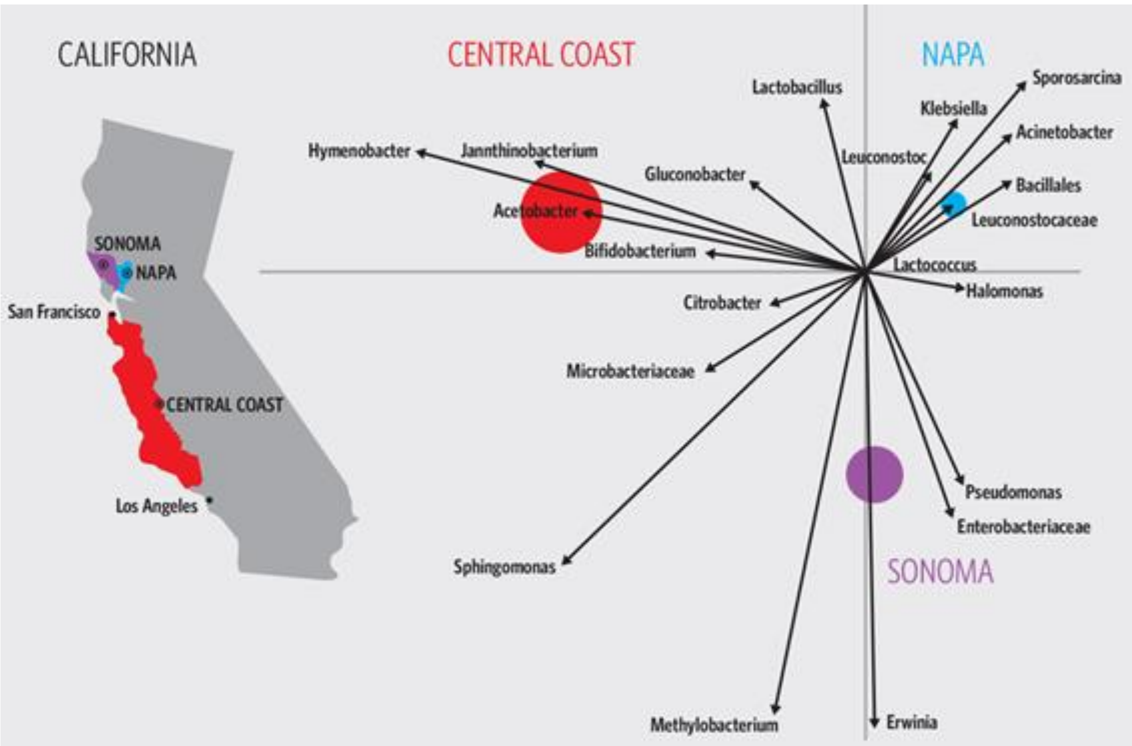

Figure 1. Differences in grape surface microbial communities present between wine regions of California. From: https://cosmosmagazine.com/earth-sciences/winemaking-art-or-science

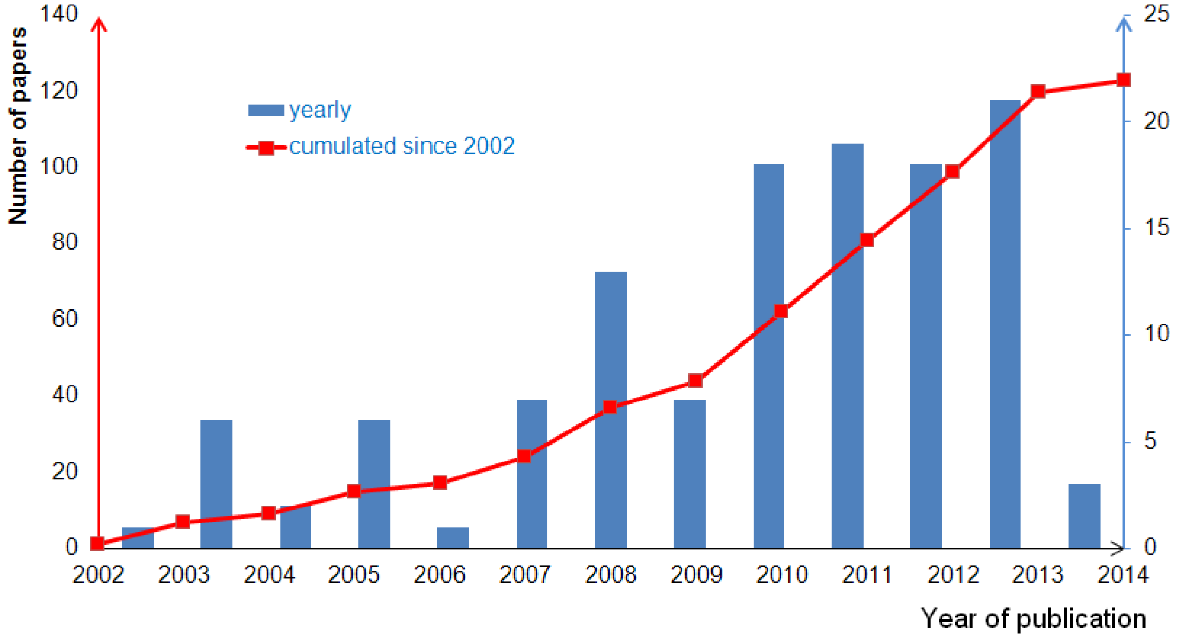

Figure 2. Increase of the number of papers (N) dealing with terroir zoning from 2002 to March 2014. Source: Web of Science (v.5.14, 2014)

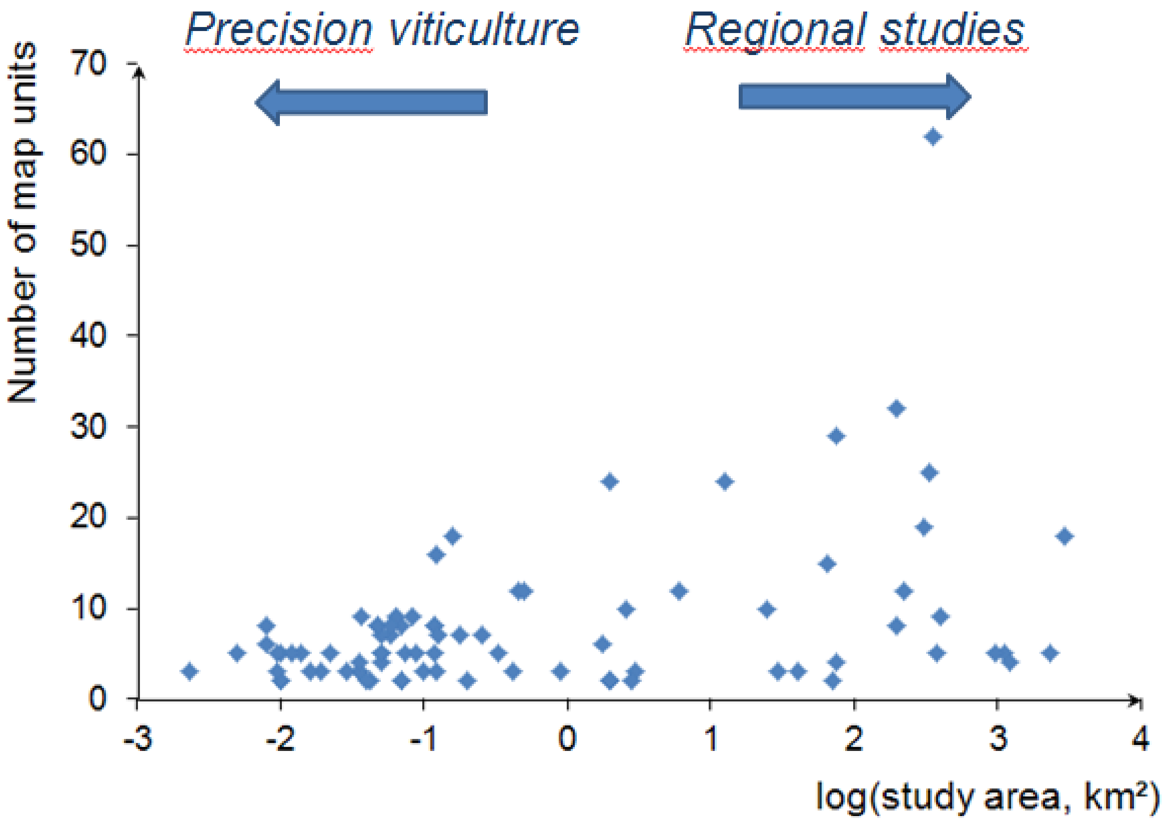

Figure 3. Plot of the number of map units vs the log of the study area in studies published from 2002 to 2014 (see Fig.2).

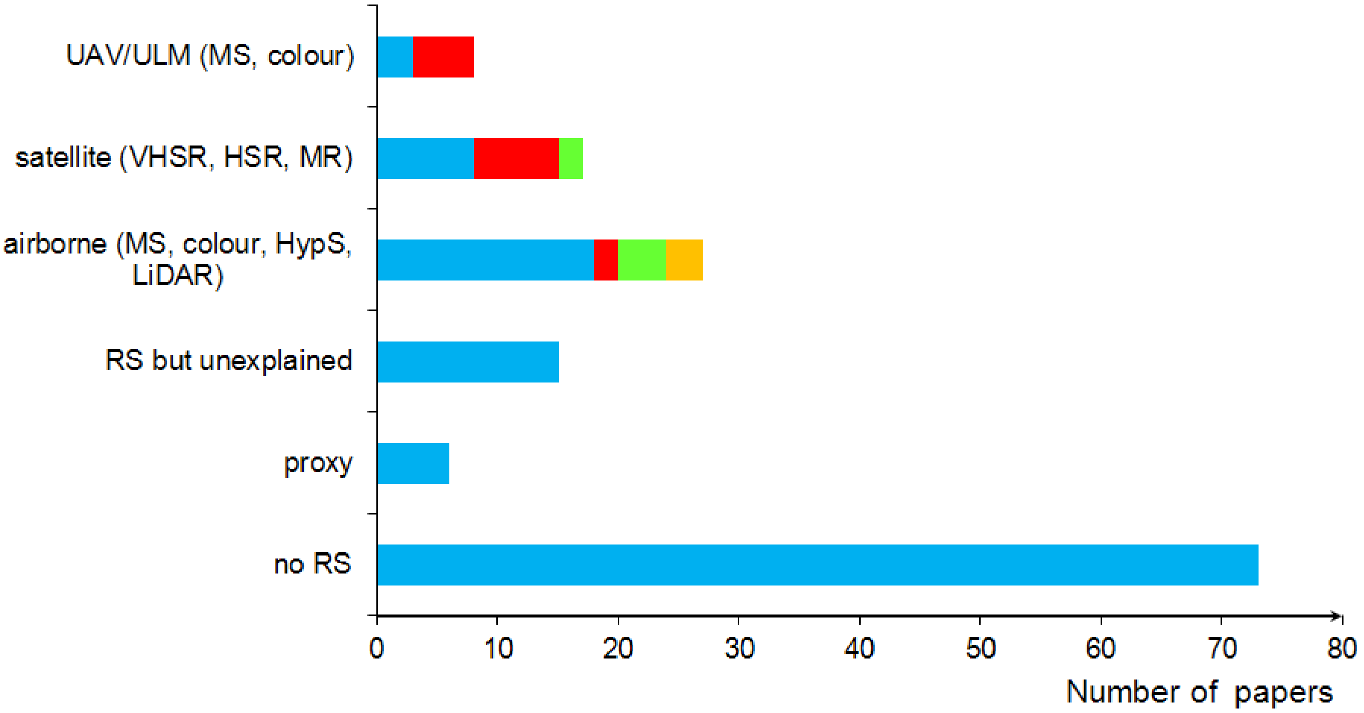

Figure 4. Use of remote sensing devices for the purpose of terroir zoning from 2002 to March 2014. Source: Web of Science (v.5.14). UAV, Unmanned Aerial Vehicle, ULM, Ultra-Light Motorized; MS, multispectral; VHSR, very high spatial resolution; HSR, high spatial resolution; MR, medium resolution; HypS, hyperspectral. “Proxy” here means reflectance measurements and/or Crop Circle NDVI and not geophysical measurements.

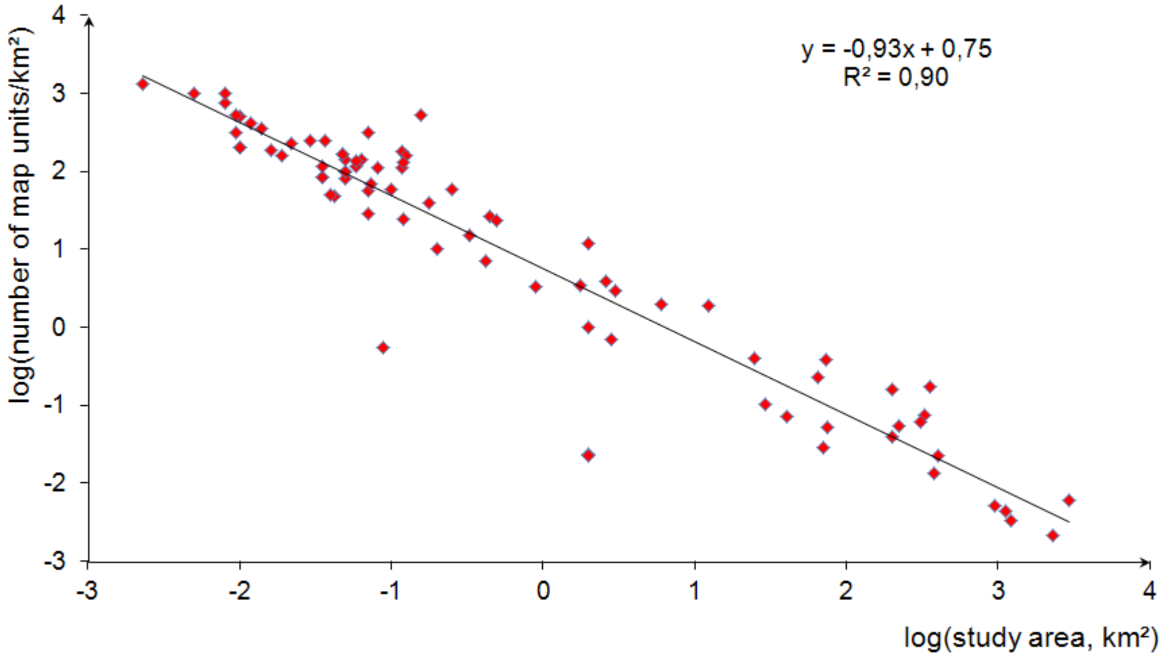

Figure 5. Relationship between the number of map units vs the study area (log-transformed variables). 2002-early 2014 period (see Fig.2).

Figure 6. Former vineyard field destroyed by erosion in the low Southern Rhone Valley, with dead vines still visible (Photograph by E. Vaudour)

Figure 7. Abandoned vineyard field colonized by native Mediterranean plant species in the Languedoc region (France), with some vines still visible (Photograph by E. Vaudour)