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Research article

Viticultural practices in Jumilla (Murcia, Spain): a case study of agriculture and adaptation to natural landscape processes in a variable and changing climate

Francisco L. Pérez*

Department of Geography and the Environment, University of Texas, Austin, TX 78712, USA

* **Correspondence:** Email: Makena@austin,utexas.edu.

Abstract: This study examines viticultural practices near Jumilla (Murcia, SE Spain). It focuses on a site with extensive rock fragment (RF) covers on vineyard soils, their probable origins and the effects surface RF have on vines and soil properties, and also discusses the expected impacts of climate change during the 21st century. Data about vitivinicultural activities, substrates, and vineyard characteristics were obtained through extended interviews and fieldwork during three summer seasons. Vineyards occupy an extensive Quaternary-age, colluvial/alluvial *glacis* at 650–760 m below Sierra Molar, an Upper-Cretaceous mountain range that supplies white dolomitic limestone and calcareous marl clasts for RF. Regional climate is semiarid; rainfall is 313 mm/year, average temperature is 14.9 °C; a significant seasonal moisture deficit (≥478 mm/year) occurs during hot summers.

Agricultural crops in the property are exclusively rainfed; no irrigation is utilized. This is facilitated by RF layers, which reach 100% groundcover and ≤30 cm thickness. Rock fragments occur naturally in the soil; RF are not placed on the fields, but accumulate by a combination of downslope transport from mountains by several geomorphic processes, and from agricultural tillage. RF covers show a layered structure; larger RF at the surface rest on a thin horizon of smaller fragments, over a thinner basal layer of even smaller particles lying unconformably on fine earth; this vertical stratification is generated by the sieving effect. The main pedological effects of RF include: improved infiltration and water storage, decreased runoff, lower evaporation rates, soil protection from rainsplash compaction and erosion, lower maximum temperatures, and greater sunlight reflection due to high rock albedo. By the late 21st century, Jumilla may experience higher seasonal temperatures, ~5–7 °C+ during summer, and 3–4 °C+ in winter, and a ~17–36% reduction of annual rainfall; the combination will cause greater evapotranspiration and vine stress. Several possible strategies to minimize the effects of climatic change are discussed.

Keywords: dry farming; limestone soils; rock fragment covers; vineyards; viticulture

1. Introduction

During the past three decades, many studies have examined the different effects that rock fragment covers have on substrates, both in agricultural and natural settings [1-3]; the agricultural literature broadly refers to these covers as gravel- or stone-mulches [4,5], but they are also called sandy fields in China [6], *arenados* or *picón* in the Canary Islands [7-9], and *gravelage* in Switzerland [10]. This study focused on the mulching effects of rock fragments (RF) on the protection of soil properties, therefore, although the mulching effects may vary with the size and number of RF present on the soil surface, here the terms RF cover and gravel mulches are considered synonymous.

It seems likely use of RF covers in different agricultural settings was initially spurred by astute farmer observations of striking associations between natural vegetation and RF-covered soils; numerous such occurrences are found in arid regions and in mountain environments [11-14], where they were noticed by early naturalists. In such areas, large amounts of rocks may be supplied by a number of geologic and geomorphic processes, including weathering, volcanic activity and mass-wasting slope processes [3,15], and plants often take advantage of these locations. The resultant biogeomorphic relationships are complex and beyond the scope of this study, but I need emphasize that use of RF and related agricultural practices are based on sound environmental principles which involve recognition and application of fundamental ecological processes.

For centuries, RF covers have been used as an aid to farming in arid areas of Argentina, China, Israel, Italy, Peru, New Zealand, Spain, and the USA [4-6,16-18]. An early agroecosystem utilizing RF was developed by the Sinagua—literally, "without water"—culture near Sunset Crater, Arizona (USA) after several eruptions during 1064–1067 AD deposited large amounts of volcanic tephra, which the pre-Columbian farmers used to inhibit soil evaporation from agricultural plots [4,5,17].

RF covers are currently used in several vineyard regions; perhaps the most widely known viticultural system utilizing GMs evolved in the island of Lanzarote (Canary Islands) following extensive pyroclastic eruptions in 1730–1736 [7]. Lanzarote farmers excavate pits ~3 m-diameter and ≤2 m-depth into the basaltic tephra down to the buried soil beneath, then add a layer of manure at the pit base; vines are planted in individual depressions, and are protected from the hot, dry NE tradewinds by low semicircular walls, built with larger fragments from nearby volcanic outcrops [8,9] (Figure 1). Vines are also grown on volcanic substrates and covered with cinder in Fuencaliente, island of La Palma (Canary Islands); vineyards are planted on broad terraces on slopes with abundant volcanic tephra deposited during the 1971 pyroclastic eruptions of Teneguía volcano [7] (Figure 2).

RF are used in non-volcanic viticultural settings as well. In Chamoson, Switzerland, farmers transport and deposit layers of gravelage, a mulch of porous limestone fragments 2–8 cm diameter, to the soil surface, to enhance infiltration and to control evaporation from vineyard soils [10]. Many vineyard RF are not added to the soil surface, as RF may already be found *in situ*, and farmers just need to manage and/or preserve them. In the Rhone Valley, France, fluvial deposits of large, rounded, white quartzite RF (*galets roulés*), are common in vineyard areas, where they reputedly act as heat sinks during the day, then reradiate this heat at night [19-21]. Along the Mosel river, Germany, dark slate clasts are present on many vineyards; some fields are completely covered by such rock

Figure 1. La Geria, island of Lanzarote, Canary Islands. Vineyards planted in fine volcanic tephra (fine gravel) deposited by the 1730–1736 eruptions. Individual vines are planted in excavated depressions; each depression, ~3 m diameter, is partially ringed by a semicircular low wall which reduces exposure to the persistent tradewinds. La-59, June 2012.

fragments, also presumed to have good heat-retaining properties and to promote drainage [20,22]. In the Douro valley of Portugal, vineyards are planted directly over steeply-dipping, foliated schist outcrops, which allow deep vine root penetration; fissures in the fractured schist fragments which make up a large proportion of soil retain much water, thus allowing vines to survive during the scorching dry summers [20].

The aforementioned associations of plants with RF-covered soils have developed, both in natural vegetation and agricultural settings, because RF offer a series of definitive ecological advantages that allow plants to survive harsh environmental—mainly climatological—limitations (see section 3.4 for summary of effects). Unfortunately, even such ecological interactions between plants and RF substrates may not provide sufficient protection against global warming, expected to further affect plant growth in the future. Several studies emphasize the changing environmental conditions impacting natural vegetation assemblages, like those mentioned above.

In Hawai'i, silverswords have declined as rainfall has dropped over the past 25 years and greater tradewind inversion variability caused drier conditions [23-25]. Shifts in circulation patterns have triggered changes in rainfall, humidity, and cloud cover [26], and pronounced warming at high elevations has affected Hawai'i during the past ~85 years [27], where a combination of lower

Figure 2. Fuencaliente, island of La Palma, Canary Islands. Vineyards planted on broad terraces covered by fine volcanic tephra (fine gravel) deposited during the eruptions of Teneguía (1971) and/or San Antonio (1678) volcanoes. LP-620, June 2010.

precipitation and greater evapotranspiration has contributed to declining silversword populations. In South America, giant Andean rosettes have been affected by rising temperatures, ~0.34 °C/decade for the past 25 years. Andean stations show lower precipitation but more frequent heavy rainfall events [28,29]. As climate becomes warmer and drier, high-altitude plants are forced to migrate upslope to survive, while woody vegetation invades from below; fire regimes also increase with higher temperatures [30]. Records show mountains worldwide have experienced severe warming during the 20th century, related to changes in global circulation [31]. Unfortunately, climate change has also affected agricultural systems, and will only get worse over the 21st century.

The purposes of this research are to: (1) examine in detail an existing viticultural agrosystem at a site associated with extensive RF covers in Murcia, southern Spain. This is presented as a specific case study that will (2) identify the main benefits of RF for vine cultivation at the study site, and (3) analyze some important agricultural management practices in the estate, emphasizing those that have gradually developed to maximize agricultural sustainability in the region. Finally, (4) I discuss some of the effects that future climatic trends in Spain and in the province of Murcia may have on agricultural practices in the study area.

2. Materials and methods

2.1. Study area and historical antecedents

This study focuses on agricultural practices on a large property (Bodegas Casa Castillo), ~9 km west of the town of Jumilla (Autonomous Region of Murcia), Spain. The study area is located on the NE section of Murcia, at 38°27′24″N, 1°25′24″W (Figure 3). This region is part of the Jumilla-Yecla *altiplano*, an elevated ~973 km^2 plateau extending from ~400 to 600 m altitude, with an average elevation of ~500 m [32,33]. The vineyards at the site occupy an extensive but gently inclined Quaternary-age *glacis d'érosion* [34,35], formed by colluvial and alluvial processes between 650 and ~760 m along the NW footslope of the Sierra Molar (941 m at summit). This small mountain range, part of the Cordilleras Béticas system of SE Spain, is an Upper-Cretaceous range composed primarily of massive, brecciated, white dolomitic limestones and calcareous marls that dip steeply toward the SE [36]. The glacis has a ~335° NNW orientation, thus Casa Castillo occupies a cooler, shaded (*umbría*) landscape position. Soils along the toposequence, developed over bedrock and mixed slope deposits, are mainly shallow Petric Calcisols [37] on the upper and middle catena sections, with deeper Haplic Calcisols further downvalley [33,38]; these soils correspond approximately to Lithic Haploxerolls and Calcixerolls in the US Taxonomy system [39,40]. Regional climate is classified as dry Mediterranean Continental, or cold semiarid steppe (BSk) in Köppen's system; annual average temperature in Jumilla is 14.9 °C, yearly mean precipitation is 313 mm (Figure 4), although it seems to have declined to ~286 mm/year over the past few years [32].

As annual potential evapotranspiration is 791 mm, there is a moisture deficit of ≥478 mm; water shortage is significant during the hot summer, whereas the rest of the year experiences a modest water surplus [41]. Regionally, precipitation and the resultant hydrological events are characterized by irregular and sporadic episodes with extreme spatio-temporal variability [38]. Vegetation upslope from the agricultural property and along Sierra Molar is a semi-natural community characteristic of Mediterranean semiarid areas; this is described below.

The agricultural property covers 413 ha (~1021 acres); of these, vineyards extend over ~228 ha, whereas almond and olive trees only occupy 62 and 17 ha, respectively. Historical records show vineyards were present on the estate by 1870 [42]; this coincided with a period of major viticultural expansion in the Jumilla-Yecla altiplano. A French winery started commercial production on the study site in 1910, as a global *Phylloxera* infestation had forced wine producers from France to look for alternative locations in Europe [43,44]. In Spain, the *Philloxera* infestation started in Málaga in 1878; although the aphids arrived in Jumilla in 1911, the altiplano largely escaped the epidemic, as the calcareous, gravelly-sandy soils common on the regional glacis slopes did not allow aphids to proliferate, because their tunnels collapse easily in sandy substrates [43,45]. In contrast, vineyards outside the altiplano, such as those in nearby Cieza, Villena and Hellin, planted on clayey soils, were significantly affected by the *Phylloxera* [32].

The family that currently owns the property acquired it in 1941, when the oldest vines now surviving were planted; however, the vineyards reached full production only in 1991, after a major property renovation allowed wine production to expand [42].

Soils at Casa Castillo, especially in the mid and lower glacis areas, are generally deep; below the surficial (10–30 cm thick) RF layers, soil profiles extend down to ~2.5–3 m depth. Although vine roots normally are concentrated in the upper soil horizons, these deep soils are advantageous for

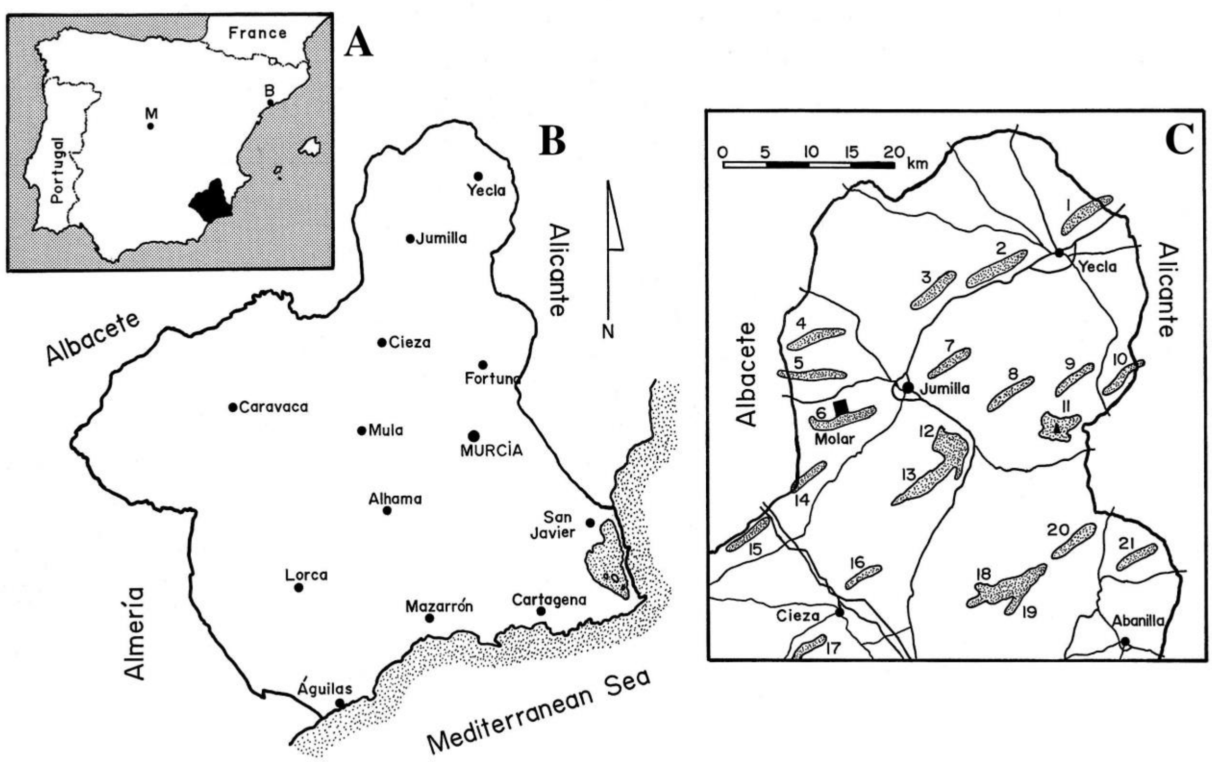

Figure 3. A. Map of the Iberian Peninsula. Dark area shows the autonomous region of Murcia; M: Madrid, B: Barcelona. **B**. Autonomous region of Murcia; dots indicate main cities and towns. **C**. Northeastern section of Murcia. Dots indicate main towns. Dark square shows location of study area. Elongated, stippled areas show the approximate location and extent of several mountain ranges (*sierras*) across the region; key for sierra names = 1: Cuchillo; 2: La Magdalena; 3: La Cingla; 4: El Encabezado; 5: Las Cabras; 6: El Molar (adjacent to study area); 7: El Buey; 8: Enmedio; 9: El Serral; 10: Salinas; 11: El Carche (El Carche peak, 1371 m, shown by a dark triangle); 12: Sopalmo; 13: Sierra Larga; 14: El Picacho; 15: Cabeza del Asno; 16: Ascoy; 17: El Oro; 18: La Pila; 19: El Aguila; 20: Quibas; 21: Barinas. National and regional roads are also shown. Scale is in km. Sources: [33] and Mapa Topográfico Nacional de España, 1:50,000, Hoja 869-I. Madrid: Centr Nac Inf Geogr Min Fomento, Inst Geogr Nac.

the extensive vine root systems. The semiarid conditions of the Jumilla region may contribute to the observed vertical distribution of vine roots. At the study area, vines commonly have just ≤5% of their roots within the upper 40 cm of soil; roots apparently are very sensitive to drought within this shallow horizon. Further below, 70–80% of the roots grow profusely in a soil layer between 40 and ~100 cm depth; these are mostly fine secondary pivoting and lateral rootlets that densely permeate the soil and extract most of the water and nutrients from it. Vines also have two to four deeper vertical roots that extend to the bottom of the soil profile, and presumably even into the underlying bedrock below; these taproots are 3–4 m, and up to 5 m, long in areas with thicker surface RF covers. Such extensive root systems undoubtedly allow vines to grow well in this *secano* fields during the exceedingly warm and dry summer season. Observations show that the root systems of individual vines extend over an area of 3.5–4.5 m^2, and in some cases they may cover up to ~5 m^2.

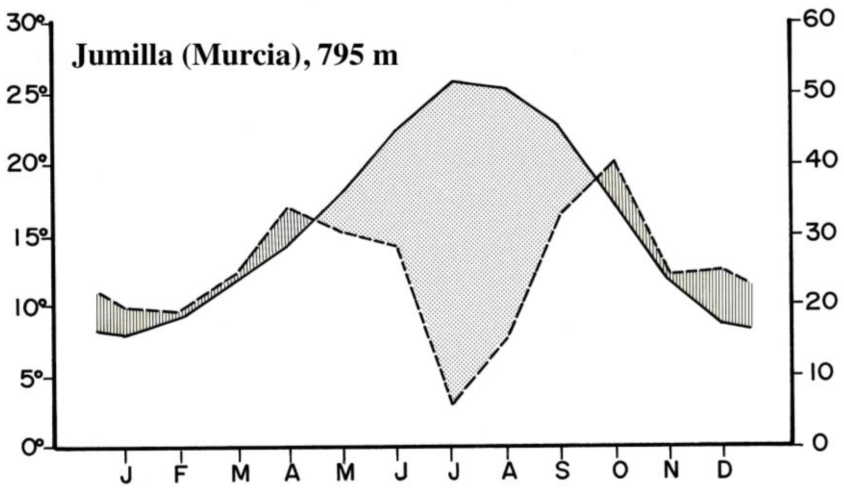

Figure 4. Climograph for Jumilla (Murcia), 38°38′N, 1°23′W, 795 m altitude. Mean annual temperature: 14.9 °C, precipitation: 313 mm/year. Solid line: temperature (14 years record); dash line: precipitation (24 years record). Season of relative water deficit is shown by finely stippled texture; season of water surplus by thin vertical lines. Source: [41].

In general, soils in the Jumilla area have a low nitrogen content, and chemical analyses also show some iron deficiency. However, despite this shortage, no chemical fertilizers are utilized at Casa Castillo; copper sulphate, applied as fungicide when needed to control mildew, is the only chemical compound used. Natural organic waste (leaves, stems, old vine rootstocks, pruned woody branches (*sarmientos*)) of vines and crop trees are mixed in with the soil, but this scanty material contributes little organic matter to soils. When tractors clean the fields after *vendimia* (time of grape harvest), a shallow plow scrapes the soil surface, and leaves the fields nearly level; this operation also uproots and kills any existent weeds, which are buried with the organic waste along a thin elongated band between adjacent vine rows. When examined, vineyards looked tidy and incredibly free of any weeds, although some places showed a narrow, discontinuous line of small invading plants, clustered along the strip where organic matter had been buried by the tractor.

Animal dung represents a more substantial fertilizer source to the vineyards. In the past (until the 1960s or the 1970s), Casa Castillo owned some 300–350 sheep; they consumed the foliage and organic matter left after vineyards and cereal fields—grown at the time in the property—were cleaned; sheep also grazed the seminatural vegetation on surrounding mountain ranges. There were also some mules—about a dozen—kept in corrals, where they were fed hay and grain. The dung of all these animals was added to the vineyards for fertilizer. Nowadays, no farm animals are kept in the property; dung from Murcian-Granadan goats—the regional breed—and from sheep is bought at local sources, composted and fermented in the estate, and added periodically—every 2 to 4 years—in the same manner as plant waste; all organic materials are introduced into the soil, immediately below the surface RF layers—at ≤40 cm depth—in between contiguous vines. Only local dung is used; acquiring dung from more distant places might introduce additional exotic weeds and/or pathogens, whereas dung from the immediate vicinity only contains seeds from local vegetation. This method of dung and organic waste placement encourages vine roots to extend laterally toward the intervening bare areas in between vine rows.

2.2. Research methods

Specific details about several agricultural practices, viticultural production, and vineyard characteristics were gathered at the property during three summers (2006, 2008, 2009). Several extended interviews [10] with various persons closely involved in the operations of the viticultural property since the late 1940s were conducted (see Acknowledgments); additional interviews with other persons, familiar with the legal regulations and laws of Jumilla's Municipality or with the local geology, were also completed. Each of the interviews, conducted both in the field and elsewhere, included up to ~65 questions and was carefully transcribed during and/or immediately after conversations.

A detailed study of soil properties and geomorphic characteristics of the vineyards and of the adjacent Sierra Molar is currently in preparation; however, some supporting field data on the RF were gathered for this study on July and August, 2009. The spatial distribution of RF covers throughout the vineyards was obtained by photographic sieving of randomly distributed plots, a widely used technique previously utilized both in a variety of agricultural and natural field settings to ascertain the percentage of RF cover and overall RF size [46-49]. A 50 × 100 cm frame was laid on the ground surface and sequential photos taken along continuous 10 m-long transects. The vertical variation of RF size with depth was determined by field excavation of sample pits ~25 × 25 cm surface area. All RF in the vertical pit were collected from three sampling layers (upper, middle, lower) and their size (intermediate = b axis) directly measured with a digital vernier. RF samples were also weighed with a digital scale to estimate total RF cover weight per unit area.

3. Results and Discussion

3.1. History of vineyards in Jumilla, and management of protected mountain areas

As noted, Casa Castillo is located along the northern footslope of a small mountain range, Sierra Molar. Like many regional ranges, Sierra Molar is occupied by public communal lands (*montes públicos* or *montes comunales*). These lands belong to, and depend from, Jumilla's municipality; the town hall (*ayuntamiento*) controls and regulates the municipality and its public lands. The sierras are controlled and legislated by the laws and statutes of the Autonomous Region of Murcia and, ultimately, of Spain. The municipality of Jumilla is the second largest in Murcia, and covers 97,238 ha (972.38 km^2); more than 1/3 of these, about 36,000 ha (360 km^2), are montes comunales [33]. The history of these enclaves of surviving semi-natural vegetation is intimately related to that of agriculture, and especially of viticulture, in the region.

Viticulture apparently started in the area after Roman settlement, around the 4th century A.D. [50], but no specific information exists until 1579, when the "*Relaciones topográficas de los pueblos del Reino de Murcia*" of King Philip II mention the existence of irrigated vineyards in Jumilla [32]. In 1667, the "*Actas Capitulares del Archivo de la Catedral de Murcia*" indicate that wine production had expanded so much that the town of Jumilla had to start paying an annual *diezmo* (10%) tax. By 1755, Jumilla already had 335 ha of vineyards, some irrigated and some rain-fed (secano). The 19th century saw a swift regional expansion of agriculture, and large-scale clearing and deforestation took place; cleared properties were distributed by public auction and largely monopolized by wealthy owners (*latifundistas*), who acquired extensive holdings. The newly cleared fields were used for cultivation of vines, olive trees, and cereals; a significant portion of the land was occupied by vineyards, especially along the piedmont of the sierras. In 1850, the Municipality of Jumilla had >500 ha of vineyards, the largest area of dry-farming vineyards in the region; by 1877, 1500 ha were devoted to vineyards [32,43]. In 1996, Jumilla had 22,500 ha of secano vineyards, which represented ~40% of the total dry-farming area (55,700 ha) in the Municipality [32]; in addition, there were 6700 ha occupied by irrigation agriculture, which included some vineyards.

The remaining non-cultivated areas in Jumilla's municipality quickly diminished in extent during the mid and late 19th century; local newspaper accounts [32] and comments by long-time residents suggest that a further expansion of vineyards took place during the first two decades of the 20th century, when the lower sections of the montes were cleared, and agriculture extended over their footslopes [32,43]. Although the sierra footslopes were owned by the larger holdings, the excessive cost of production prevented their owners from directly cultivating them; instead, they leased them to small farmers (*colonos*), who did not have their own land and were forced to rent small parcels of land [32].

These footslope areas were longitudinal strips (*franjas*) parallel to the base of the mountains, and commonly were ~100 m wide, although in some areas they were somewhat narrower or wider, depending on local topographic gradient. Colonos paid the owner 1/6 of their crop production; the owner could simply collect the grapes during the vendimia from each *sexta hilera* (6th row) of the vineyard, as payment for the rent. Individual colonos cultivated 2000 to 4000 vines, but a few may have tended up to ~6000 vines. In essence, colonos occupied elongated franjas on private lands that were not utilized by their owners, but colonos never cultivated the communal lands. At Casa Castillo, colonos formerly rented a long footslope strip of land below Sierra Molar, but the estate eventually bought them out, and acquired the rights to use this land. Although this franja area still remains largely uncultivated, the winery owners did not want colonos to interfere with, or hinder, any agricultural operations. In recent years, small portions of the franja have become gradually occupied by new vineyard plantings, as the property has expanded its viticultural activities.

Sierra Molar is now covered by an impoverished semi-natural vegetation, a remnant of the formerly denser and more extensive forests of Aleppo pine (*Pinus halepensis*, locally known as *carrasco*) and a few *enebros* (*Juniperus oxycedrus*) and *sabinas* (*Juniperus phoenicea*). Lower stature vegetation is dominated by a tough perennial grass, *esparto* (*Stipa tenacissima*) and by a variety of shrubs, including rosemary (*Rosmarinus officinalis*), thyme (*Thymus vulgaris*), buckthorn or *espino* (*Rhamnus lycioides*), *lentisco* (*Pistacea lentiscus*) and *almohadilla de pastor* (*Erinacea anthyllis*) [50,51]. Esparto has been economically important in the region since prehistoric times [52,53], and was locally exploited and gathered from the communal montes for the manufacture of ropes and numerous kinds of woven crafts, including rugs (*esteras, baleos)* and baskets *(capazos, cernachos)*. Esparto use ended in the 1960s to early 1970s, as it was replaced by synthetic fibers and other materials. Today, esparto may be occasionally gathered from the montes for use in small arts and crafts—in which case collection permits have to be issued by Jumilla's Ayuntamiento—but it's no longer commercially exploited. As one informant succinctly put it: "esparto is not used anymore".

Casa Castillo owners appear not to interfere with the vegetation of Sierra Molar in any way; although numerous pines have been planted in the lower sections of the property and near the farm buildings, there has been no reforestation, plantation, tree cutting, or any other kind of vegetation modification, in Sierra Molar. Pine forests there are extensive and relatively dense (Figure 5), but most trees have medium-size trunk diameters—at best—and pine stands appear to have a fairly uniform age-distribution, somewhere within the 40–60 year range (in 2009). This might imply that some extensive fire(s) burned a substantial area of the Sierra Molar sometime in the 1940s to 1960s, but I have not found any records that could corroborate this hypothesis.

Figure 5. Vineyards on the uppermost section of Casa Castillo, adjacent to the base of Sierra Molar; Pico Molar, in background center, is 941 m high. Slope angle on this steep vineyard (Las Gravas) is ~7°, ~755 m altitude. CC-408, Aug. 2009.

3.2. Origin and development of rock fragment covers

All crops in this agricultural property are grown as secano, without any kind of irrigation; vines, and almond and olive trees, grow well with the moisture stored by the soils, although almond trees appear somewhat less resistant than vines, and are more easily affected by drought. Most of the vineyards, and all of the almond trees, are planted on areas where extensive RF layers completely cover the soil surface (Figures 6, 7); this is a common practice in northern Murcia's agricultural fields. The few olive trees on the property occupy the distal segment of the glacis, where soils contain only a sparse amount of clastic fragments (Figure 7).

The RF covers found on this property are those naturally occurring in the soil; RF are not placed, added, redistributed, or transported to the fields in any way; the estate owners believe any RF management would be extremely difficult and prohibitively expensive. In addition, there is no

Figure 6. Almond-tree grove on soils completely covered by limestone fragments, on the upper glacis segment; slope angle is ~4°, 715 m altitude. CC-233, July 2009.

attempt to manipulate RF size, thickness, structure, or layering. Surface RF are abundant at the estate; they presumably accumulate by a combination of natural and agriculture-induced processes. Methodical field exploration showed that surficial RF are exceedingly abundant behind vineyards on Sierra Molar, where they have been produced by weathering of extensive limestone outcrops and of subsoil bedrock. In many places, RF appear to have gradually moved down steep slopes, and accumulated along the bases of cliffs, prominent outcrops, and on mountain footslopes (Figure 8); from there, clasts have been transported by different natural geomorphic processes—which must have taken place over long time periods—down the gentle glacis gradient.

I also examined several parcels contiguous with the highest vineyards, on the upper glacis areas (~750–760 m). At the time, some large sites were being prepared for new vineyard plantings; prior to this, parcels are *desmontadas* (literally, to remove the existing semi-natural monte vegetation). New areas are made ready for planting after clearing, by hand, the sparse semi-natural vegetation covering them—esparto grass, shrubs, herbs—before any kind of machinery is used. The ground surface on the cleared parcels inspected was covered with nearly continuous RF layers, that looked exactly like those on adjacent established vineyards.

Figure 7. Olive tree grove on soils with a modest cover of marl and limestone fragments, on the lower glacis segment; slope angle is ~1.5°; ~650 m altitude. CC-334, Aug. 2009.

RF covers are most extensive on the slopes immediately below Sierra Molar and on upper vineyard plots (~760 m), where surficial RF reach 100% cover—this area is henceforth called *Las Gravas* (The Gravels). RF cover all or most of the ground surface down to about the lower-middle glacis (~675 m altitude) (Figure 9). Percentage of RF cover gradually decreases downslope, to ~0–10%, on the distal sections of the colluvial glacis (see Figure 7). Depth of RF covers varies from ~10 to almost 30 cm; RF layers exhibit a complex internal structure, with three different layers of unequal thickness: at the surface, large RF (≤80–100 mm) are followed by a slightly thinner horizon of smaller fragments (≤45–50 mm); below, lying unconformably over fine earth, a thin bottom layer of finer RF (≤25–30 mm) is found (Figure 10). The well-sorted layers are generated by the sieving effect [48,54] whereby fine grains trickle downward while coarse clasts are displaced upward within the soil profile, by a combination of both natural processes such as gravity, runoff and throughflow, mixing and sorting during downslope movement—i.e., kinematic sieving [55,56]—frost activity in winter, thermal creep during summer [3], faunal and floral (root) pedoturbation, and agricultural disturbance by machinery, as discussed below. RF covers constitute a substantial portion of the substrate at Casa Castillo; for the 16 cm-thick layer sampled above, total weight reached 205.9 kg/m^2, or ~2059 t/ha.

Figure 8. Soil surface, covered by limestone rock fragments, on a steep slope (~27°) of Sierra Molar, ~880 m altitude. The photograph covers an area ~2.2 m-wide; most RF are from ~3 to ≤10 cm long. CC-522, Aug. 2009.

3.3. Role of agricultural equipment in the development of rock fragment covers

Although RF at the study area ostensibly result from natural processes, some agricultural activities also contribute to RF concentration on the soil surface. After new areas are initially cleared for planting, RF are largely left *in situ*; only larger rocks (≥40–50 cm diameter) that might make plowing difficult are removed, and some are used to build roads, demarcation walls, or *racillos*. The

Figure 9. View of a ~50 × 50 cm area of the ground surface, covered by limestone RF; mean RF size (b axis) is ~46 mm. Scales are in cm and dm. CC-82, July 2009.

estate manager briefly considered breaking larger RF down to a more optimal size, and adding them to the existing RF, but the experiment was never tried out. Racillos are retention walls and paved covers on steep slope areas, intended to diminish or prevent soil erosion by runoff during rainstorms; RF are broken or cut by hand, and then fitted in the racillos one by one, with hammer and pick. Some racillos in the property are more than a century old, and have been very efficient in controlling soil erosion.

As the technical director of the estate explained, once a parcel is cleared, a flat, shallow metal plank—a "line", not a plow—that penetrates just ~15 cm into the ground is run over the new plot to loosen and turn a thin surficial layer; thus, deeper soil horizons are not disrupted and remain largely undisturbed. Such mechanically-induced process of kinetic sieving [46,47,57] contributes to the upward migration of larger clast fragments. After this procedure, the ground appears as a heterogeneous mixture of RF and fine earth, but a single rainfall event suffices to transfer soil grains downward through the crevices between clasts, and the soil surface afterwards presents an openwork layer of coarse fragments [58].

Other than small tractors, no further equipment is used to work the vineyards; vine rows, ~2.6 to 3.2 m apart, are sufficiently separated for the narrow machinery to pass through. However, every few years, soils between vine rows become gradually compacted, and their infiltration rates drop. Soils must then be ruptured to reestablish and maintain structure; this is done at the end of summer, when soils are very dry. Such tillage cannot be accomplished in winter, when soils are moist and do not

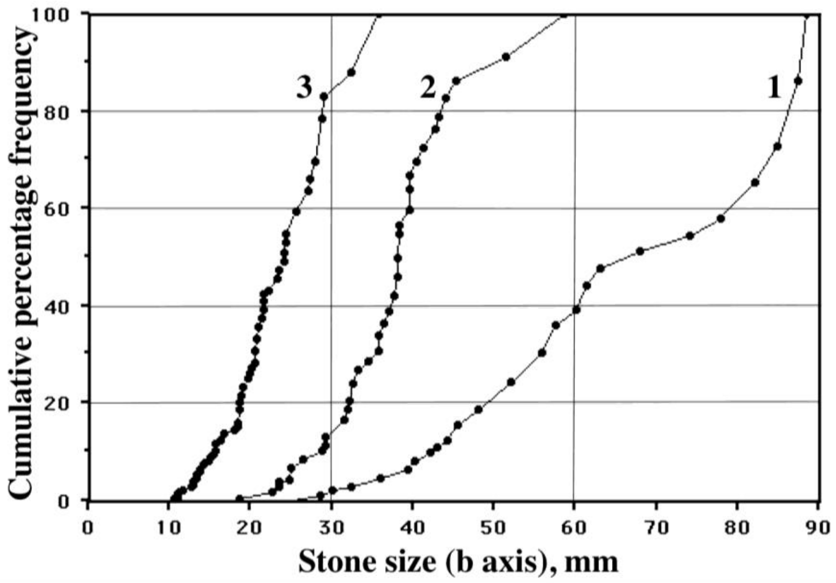

Figure 10. Granulometry (cumulative percentage frequency) of RF size (intermediate = b axis) for a 16 cm-thick RF cover over soil, sampled at three different depths. Key: Upper horizon (1) = 0–8 cm; middle horizon (2) = 8–13 cm; lower horizon (3) = 13–16 cm. Graphic Median (D_{50}) RF size: 1 = 65.6 mm; 2 = 38.2 mm; 3 = 24.4 mm. Slope angle: 4.5°, 655 m altitude.

break into chunks or peds; the treatment increases soil infiltration rates, and helps the growth, elongation, and soil penetration of vine roots. Even then, the fine earth fraction of the soil and RF are not thoroughly mixed; a tractor with a three-pronged duckfoot chisel rakes the soil down to ~60–70 cm depth; this process undoubtedly helps to further reinforce and build up RF covers. Unlike RF at Casa Castillo, the RF covers found on many Petric and Haplic Calcisols in Murcia have resulted from widespread agricultural disturbance involving rupture of C soil horizons after deep plowing, which detaches clast fragments from deep soil layers [33].

3.4. Effects of RF covers on soil processes and grapevine growth

Surface RF covers provide several important geomorphic, hydrologic, microclimatic, and biological benefits to crops. Some of the effects identified at Casa Castillo, and elsewhere, include the following:

(a) A RF cover improves infiltration rates, depth of water penetration, and total soil-water storage. Owing to greatly increased macroporosity at the ground surface, openwork layers of rock fragments are highly permeable, thus able to absorb much water quickly [8,15,58]; this not only increases overall infiltration rates, but the total amount of water captured by the ground surface [10,59]. In addition, water penetrates more deeply into the soil [58]. Infiltration is encouraged by greater RF size (average diameter range: 15–140 mm), as voids between RF also become increasingly larger [60,61]. For loose, nonembedded rocks, infiltration rates also increase as the percentage of RF cover increases [62]. All these closely interrelated processes result in greater water storage capacity under the RF layer.

At Casa Castillo, it has been noticed that even during torrential rainstorms (≤140 mm rain), soils at Las Gravas, protected under thick RF covers, allow ample infiltration, and no runoff is generated, thus soil erosion is effectively curtailed. In contrast, soils on the lower-slope vineyards, with a sparse or no RF cover, produce much runoff, thus quickly contributing to soil erosion and flooding events (see (c) below).

(b) A RF cover efficiently lowers evaporation rates, and extends the time period of high soil-water content. This is probably the most frequently mentioned effect of RF covers [1,63-66]. Numerous cumulative evaporation measurements, both during laboratory trials and in agricultural plots, have shown significant differences between soils under RF and bare ground. Uncovered soils in Tanzania experienced, over a 39-day period, water losses five times greater than adjacent soils insulated by thin layers of volcanic scoria [67]. Experiments using Hawaiian tephra [68] indicate bare soils lost 50% of their water after just 9–14 hr evaporation, whereas soils shielded by RF (5–34 mm diameter) reached the same water content in 112–191 hrs.

A 2-year study of high-altitude tea plantations in Kenya [69,70] found the moisture content in plots covered by RF (≤12.5 mm diameter) during the dry season was ~25%, but only ~8% in uncovered parcels. In a maize plantation in Ethiopia, soil moisture below a 5 cm-thick layer of RF (3–5 cm diameter) was higher than in adjacent bare ground; as a result, grain yield was four times greater in the insulated soils [71]. Soils protected by RF (2–10 mm diameter) in barley fields of Jordan [72] maintained a water content of ~22%, and yielded almost twice as much grain as contiguous bare soils, with only 12% moisture. In Lanzarote's vineyards, a 10 cm-thick tephra cover (1–6.3 mm diameter) reduced, over a 31-day period, total evaporation by 92%, when compared to exposed soils [73]. The upper horizons of cinder-covered soils contained 8 times more water than those in control plots; insulated soils remained above the wilting point all year-round within the root zone of vines, whereas bare soils did not [8, 9]. Large contrasts in moisture content were measured throughout the year at all depths; moisture regimes were very different: covered soils had a Udic (moist) regime [39], whereas exposed soils showed an Aridic regime, and remained dry for >50% of the time [74]. In most studies, evaporation rates decrease proportionally with greater thickness of the superincumbent RF layer [15,65,75].

At Casa Castillo, upper-glacis soils at Las Gravas provide a greater and more steady water supply to plants than bare soils further down the glacis gradient. Vines in this area are planted at a much greater density—3000–3400 vines/ha—than in the lower, exposed soils, that can support only 1000–1200 vines/ha; thus grape productivity—and, reputedly, even wine quality—is greater in the former vineyards. Due to a lower summer drought incidence, Las Gravas area suffers much less from vine death than areas devoid of RF, where vines succumb more easily to desiccation. For example, out of 4000–5000 vines in Las Gravas, only 5 or 6 (~0.1%) were lost during the 2007–2008 season. In comparison, losses in the lower vineyards commonly are 3 to 4%, and even in good years never drop below 2%; thus vine death is 20 to 40 times greater than in RF-insulated areas. Soil moisture is essential in determining the start of root growth in spring [21,76]; grapes in Las Gravas consistently grow better, and ripen earlier, than in bare-soil areas; this is probably related to efficient water conservation.

At the same time, greater soil-water storage at Las Gravas can occasionally become a problem. From a viniviticultural perspective, it is optimum that vines reach a moderate hydric stress, as the plant in that state produces greater amounts of metabolic compounds beneficial to the quality of the grape juice and the resulting wine [76]. However, some years, rains may occur right before vendimia harvest—around mid to late August—and soil profiles at Las Gravas become excessively moist;

when this happens, harvest must be postponed 7 to 10 days, until grapevines have reached again a moderate water deficit [76] [JM Vicente Sánchez-Cerezo, 2009, personal communication]. In some unusually rainy years—about once a decade—intense storms close to vendimia saturate soils under RF. Grapes then quickly become hydrated and swollen, causing many grape bunches to become crowded, and berries start bursting; juice now oozes from them, which attracts mosquitoes, and soon afterward grapes rot. That year, the whole harvest may be lost.

(c) RF covers protect the soil surface from rainsplash disturbance and soil compaction, and decrease runoff, sediment transport, and soil erosion. By intercepting raindrops and lessening their kinetic energy, a RF cover efficiently protects the soil surface from rainsplash; this reduces breakdown of soil ped aggregates [1] and the subsequent sealing of surface textural or structural pores by detached fine grains [18,77,78]. In exposed soils, these processes also contribute to compaction and the formation of surface crusts [59,60]. As RF covers efficiently stabilize the soil surface, rates of soil erosion and sediment yield are also lowered in RF-covered areas [2,79]. In some Murcia areas, marl-derived soils, often found on lower-glacis catena segments, show a fairly high level of compaction at the surface, produced by rainfall and runoff, which encourage the formation of a strong laminar crust [52].

At Casa Castillo, lower-slope soils, largely developed from marl and mostly unprotected by RF covers, show prominent soil crusts and widespread miniature features associated with soil erosion. Cohesive crust plates, ~3–6 cm long and 8–15 mm thick, can be easily lifted from the ground surface, which is often also covered by tiny, 4–5 mm tall soil knobs and micropedestals, shielded from rain under isolated RF; all these features are known to result from rainsplash compaction.

Measurements of soil shear strength show that soil compaction is appreciably greater in bare areas (362.4 ± 72.2 g/cm^2) than under RF covers (194.3 ± 60.1 g/cm^2); these differences are statistically significant ($p < 0.0001$).

(d) A RF layer influences maximum diurnal and minimum nightly temperatures of soils below. As rocks have greater heat capacity than dry soil, they significantly affect heat flow through the substrate, and tend to attenuate thermal extremes [1,3,70,80]. During diurnal heating, RF shield the ground from solar radiation, and soil temperature under them remains cooler than in exposed areas; during nighttime cooling, the effect is reversed: RF retain and reradiate heat, and soils below them stay warmer [81]. Many RF studies have measured lower daytime temperature maxima under RF [15,61,64,70,82,83], and some also report higher nightly minima, suggesting RF covers may offer some protection against extreme cold, including frost events [10,64].

RF color may greatly affect maximum temperatures, as soils under dark RF are not as effectively protected from high temperatures as those below lighter ones [21,61,64,70]. This is referred to as the albedo factor [65]: as light-colored rocks reflect a greater percentage of sunlight, they remain significantly cooler; differences between white and gray rocks may be as high as 13.1 °C [1,84]; see also (e) below. The reduction of maximum soil temperatures interacts with soil moisture in at least two important ways. As peak temperatures are lowered, evaporative losses are further diminished [64], thus helping conserve soil water (see b above). In addition, the fact that soils below RF remain more humid also influences their temperature: moist soil needs more heat energy than dry soil for its temperature to increase, thus remains cooler for longer periods [21].

(e) Additional effects of RF covers. Following the Munsell color system [85] the light-colored limestone RF covers at Casa Castillo are predominantly white (10YR 8/1 or 7.5YR 8/1) to very pale brown (10YR 8/2) and pinkish white (7.5YR 8/2). In comparison with darker adjacent bare soils, largely brown to light yellowish brown (10YR 5/3 to 6/4), RF covers have a much greater albedo, thus reflect a higher percentage of incident light back to the vine canopy; this encourages the uniform ripening of grapes, as it adds much light from underneath and within the grape clusters. However, excessive light reflection might also aggravate heat injury on grapes during extremely hot summer days [76].

Thick RF covers also appear to inhibit unrestricted weed growth at Casa Castillo. This beneficial effect has also been reported for vineyards in Switzerland [10], although studies in the USA [65] mention the greater soil moisture below rocks tends to encourage weed growth through the RF. Studies of vineyards in the hyperarid islands of Lanzarote and Fuerteventura [9,86] report a substantial reduction in salinity and sodicity for soils under RF, related to modifications in soil moisture regime caused by the RF, which increase infiltration and reduce evaporation and upward movement of Na and other salts.

3.5. Soil depth and vine roots at Casa Castillo

Vines are perennial plants that have evolved to probe a large soil volume with a low overall root density, thus grapevines develop extensive root systems vertically and laterally; this should maximize the probability of finding available resources, such as water and nutrients [21,87]. Vines derive most of their sustenance from the upper soil horizons; extensive studies [20,21,88] indicate that vines growing in deep, fertile soils develop ~63% of their roots within the upper 60 cm, and less than 20% of total root length is found below 1 m depth. In older plants, some roots penetrate >4 m through porous, sandy soils, and limited data indicate vine roots may extend down to 6 m in very deep soils.

Growth of lateral roots is normally restricted to ~1.5 m from the trunk; the main, thicker lateral roots within the top 30 cm of soil normally become established by the 3rd year, but smaller "feeder" roots continue to grow vertically and horizontally from these main roots [21,87]. A dense root network within topsoil can extract water efficiently from surface horizons, and vines are able to tolerate dry soils due to their ability to selectively expand their roots toward soil patches with available water [76]. This strategy may suffice for "normal" dry periods, but during considerable drought episodes vine roots draw significant amounts of water from even >2 m depth, to make up for intense transpiration losses [20]. The roots of drip-irrigated vines become concentrated near water emitters, but in rain-fed secano plants, roots are normally much more widespread. In non-irrigated soils, roots extend into deeper soil horizons; and water uptake gradually shifts to these deeper soil layers as the soil dries, then returns to the upper layers after rainfall events wet the topsoil [76].

4. Expected environmental adaptations of viticultural practices due to climate change

4.1. Climate changes in Spain during the 20th and 21st centuries

Since reliable climatological records started in ~1850, mean global surface temperature has increased by ~0.8 °C; most of this rise has taken place after 1950, as the period 1950–1999 saw an increase of ~0.6 °C [21]. Climatic change has influenced temperatures and precipitation in all regions of Peninsular Spain—including Murcia—and the Canary Islands, and is expected to continue affecting these parameters. Since the start of the 20th century, the Iberian Peninsula has experienced an overall rise in temperatures, especially in its southern, southeastern and eastern parts [89].

Although there is a broad range of regional variation, average annual temperatures in Spain have increased, especially since the 1970s, by an amount higher than that observed at a global scale [31,90,91]. Records for the 20th century indicate a gradual increase in temperature for the Iberian Peninsula particularly pronounced during the period 1975–2005, with a rate of warming close to 0.5 °C/decade; this is ~50% higher than the continental average for the northern hemisphere, and almost three times greater than the global average. Warming has affected all seasons, but during the last 30 years, heating has been more pronounced in spring and summer [92]. During the same period, yearly precipitation has dropped significantly, mostly due to lower rainfall amounts in winter; the downward tendency is most pronounced for the southern Iberian Peninsula and the Canaries. Interannual rainfall variability (IRV) has also increased. The combined trends for temperature and rainfall have resulted in greater evapotranspiration [91,92].

The North Atlantic Oscillation (NAO) is a pattern of variability in atmospheric circulation that strongly affects climate in the Iberian Peninsula; NAO is closely associated with precipitation and with temperature variations on an interannual and decadal basis [91]. Climate simulations project an increasing NAO trend for the 21st century, which would result in a declining precipitation in the Iberian Peninsula, especially in the southern half. The ESCENA project of the University of Cantabria (Spain) forecasts a continued rise in temperatures for the first half of the 21st century that will be even more significant than that during the second half of the 20th century [91,93]. Climate projections for the late 21st century are even more pessimistic, predicting substantial increases in average seasonal temperature, greater in summer (6 °C for worst-case scenario) than in winter (2–3 °C). A drop in precipitation during the whole year, also larger in summer than in winter, is expected as well [91].

4.2. Climate changes in Murcia and the Jumilla area

Due mainly to its latitudinal extent and complex topography, Spain displays a broad climatic diversity; accordingly, climate changes will have different impacts on its various regions [90,91]. Unfortunately, the southeastern Peninsula will be affected by harsher environmental changes. Records for 23 stations in the Segura River basin (Murcia) during the period 1940–1997 show a pronounced tendency for rising temperatures starting in the 1970s, associated with intensification of anticyclonic situations; spring showed the greatest seasonal increase in maximum temperatures, ~0.123 °C/year [90,94]. Extreme regional warming will continue, and by the year 2050, the total rise in temperature for northern Murcia and the Jumilla area will be ~2.3 °C, while annual precipitation will drop by ~15% [91]. Two long-term scenarios of global CO_2 emissions have considered probable regional climate changes in Spain; in the first, global CO_2 concentrations would rise to 760 ppm by the year 2100 (about double than now), and for the worst-case scenario, CO_2 would reach 850 ppm. These models suggest that, by the end of the 21st century, northern Murcia and the Jumilla area might experience a rise in average seasonal temperatures of ~5–7 °C during the summer, and 3–4 °C during winter months. The frequency of days with extreme maxima will also increase; this is expected to be more pronounced in spring [90,92].

Rainfall changes are also expected, but these will have a complex geographical pattern; a decrease in annual precipitation, greater in summer than in winter, is forecast for northern Murcia. Detailed maps [90] show the northern Murcia/Jumilla area might see a yearly reduction of 54–112.5 mm precipitation; this represents ~17–36% of the present annual rainfall. Interannual rainfall variability will also probably increase; this may seriously reduce water input in some years, as the

IRV for the Iberian Peninsula is already greatest around the Mar Menor region of southern Murcia, where it reaches a variation coefficient of ~40%. Moreover, the number of days with extreme precipitation events (>150 mm) is expected to rise during the period 2011–2030, with consequent increase of soil erosion and flooding events [90,91].

4.3. Climate change and effects on vine growth

Climate change during the second half of the 20th century has affected many vine-growing areas worldwide; further changes are projected to have dire effects on viticulture [95]. Records from 1952 to 2006 in the Alt Penedès (NE Spain, Catalonia) show an overall grape growing-season warming of 1.0–2.2 °C, with a significant rise in heat-accumulation indices due mostly to a greater number of days with peak diurnal temperatures [91,96]. Observations in Bordeaux, France between 1952 and 1997 also evince a trend of reduced precipitation during the season of grape maturation [97]. Atypical dry spells and/or periods of deficient rainfall are also reported from vineyards in Romania [98]. The combined temperature and precipitation trends have resulted in lower soil moisture, greater evapotranspiration, and higher vine water consumption [76,99]. Analysis of vine evapotranspiration rates in Catalonia indicates that for each 1 °C increase in temperature during the growing season (Apr–Oct), water demand by vines rises 6 to 14% [96].

Higher temperatures accelerate vine growth and development, thus phenological stages occur in more rapid succession than under cooler conditions [76]; consequently, rising temperatures have resulted worldwide in faster grape growth and earlier ripening [21,100]. Statistically significant trends for an earlier maturation date were found in ~98% of all sites studied in Australia, where ripening date advanced ~8 days/decade between 1985 and 2009 [99,101]. Earlier ripening, also by 8 days/decade (1972–2004), was found in Colmar, France, and by four days/decade (1955–2004), in Geisenheim, Germany. Similar outcomes are reported from Bologna, Italy [102], Bordeaux, France [97] and Languedoc, Mediterranean France [100].

Besides rising temperatures, climate models predict that changes will occur in the number and extent of extreme weather events. Summer heat waves will likely increase both in frequency and severity, as the probability for an event of 5 consecutive days over 35 °C doubles for a 1 °C warming, and increases by a factor of five for a 3 °C warming [76]. Temperatures >40 °C cause a sharp drop in vine photosynthesis due to chloroplast disruption; leaf temperatures >45 °C, even for brief periods, cause a rapid decline in stomatal conductance and photosynthesis, and if such high temperatures persist over prolonged periods, they can kill grapevine leaves. Leaves are more susceptible to heat waves during periods of water deficit; brief episodes of extreme heat are worse than longer periods of moderately high temperatures [76].

Alterations of plant canopy and/or grape bunch microclimate following leaf death might trigger several complex responses, including loss of vine vigor, further inhibition of photosynthesis or of berry development, berry sunburn or heat damage, decreased synthesis of berry components, inhibition of ripening, loss of fruit volume and yield, and possible increase in sugar concentration, thus alcohol concentration of the resultant wine [99,100,103]. A further side effect of rising temperatures is that some warmer grape-growing areas might reach—and probably are already approaching—the upper limit of the grape types they can grow. Varieties like Syrah, Garnacha, Cabernet-Sauvignon, or Monastrell, traditionally fit for hotter climates might start showing some of the problems mentioned above [76,103,104].

4.4. Responses of viticultural practices to climate change

The extreme climate changes expected for the remainder of the 21st century will undoubtedly strain agriculture sustainability in the northern Murcia/Jumilla area. Following Huglin's heliothermal index—originally developed for European viticulture areas—Jumilla's climate would change in the period 2031–2050 from a temperate-warm regime to warm, with nights changing from cool to temperate, whereas the precipitation regime would switch from moderately dry to very dry [90].

Jumilla's climate is fundamentally characterized by low annual precipitation, with a high interannual variability that can sometimes exceed 100% [105]. As noted, secano agriculture at Casa Castillo relies entirely on rainwater; this substantially limits the ecological impact this property might have on regional water resources, already severely stressed. The Jumilla-Yecla altiplano has no permanent water courses, and the only available water is that withdrawn mainly from four regional aquifers; La Cingla and Jumilla-Villena (J-V) aquifers are the sources of water for Jumilla [105,106]. Regional groundwater exploitation started in the late 19th century, and has accelerated ever since; currently, the larger altiplano aquifers are severely depleted, as water extraction greatly exceeds recharge [105,107,108].

For the J-V aquifer, 53.3% more water is used than recharged at present [109]. Piezometric levels have dropped dramatically in these aquifers, up to 200 m over a 30-year period, and in some sectors the rates of descent have exceeded 10 m/year; these figures are among the highest in Spain [33,105]. The J-V aquifer fell ~95 m between 1980 and 2007 (average: ~3.5 m/year); groundwater descent in La Cingla was lower, ~1.3 m/year during the same period. If groundwater use continues unabated, the piezometric levels would continue to go down until aquifers are physically exhausted. The J-V aquifer would reach a zero-mean annual groundwater recharge in 2070 or 2080, and would have just an 8.8% chance of total recovery within the next 100–200 years; the Cingla aquifer has just 0.74% of probability recovery in that period. Even if water pumping stopped today, it would take 25 years for the Cingla aquifer, and 47 years for the J-V aquifer, to restore their former levels of a natural regime [105,109].

Agricultural irrigation consumes the largest share of pumped groundwater in the region [108]. Out of 45 million m^3/year extracted from the J-V aquifer, 84.4% are used for irrigation; 83.3% of the 30 million m^3/year pumped from La Cingla are used for agriculture [105]. Despite this, viticulture contributes little to aquifer depletion, as most vineyards in Jumilla's municipality use dry farming. Secano vineyards cover ~7039 ha and represent 25.2% of all crops, yet require only ~7.2% of the pumped water. In contrast, non-citrus fruits occupy 35.4% of plantings, but consume ~58% of extracted water—thus use nearly six times as much water per ha as wine vineyards [105].

Unfortunately, even secano vineyards may be affected by the grim scenarios of diminishing rain, increasing rainfall variability, rising temperatures, and greater evapotranspiration rates the 21st century will bring to the region [110]. A recent case study of drought effects on rainfed agriculture in Jumilla [111] found droughts currently last as much as 9–20 consecutive months. Use of the SPI (Standard Precipitation Index) [112] revealed the drought from June 2006 to Feb 2008 reached an astounding SPI of −23.76; values lower than −1.65—the highest SPI category—are considered "extreme" in their severity.

In order to adapt to some of the potential effects of climate change, two sets of strategies may be open to viticulturalists [91,95]: either vineyards are relocated to new, cooler geographical locations, or some cultivation practices are judiciously modified. Shifting vineyards to landscape positions with more northerly or easterly orientations to reduce insolation and ambient temperatures [91] would be a reasonable strategy, but Casa Castillo already occupies an umbría site. Moving vineyards to cooler locations either at greater elevations or higher latitudes may make sense from a national perspective, but it is probably not a realistic option for regional Jumilla viticulturalists. Mountains in the altiplano either do not extend much altitudinally, or are too steep and have abrupt topography. Moreover, this approach would encroach upon, and reduce the extent of, the remaining regional pockets of semi-natural vegetation, which would in any case be subject to greater ecological pressure from drought and from the increased fire regime frequency that should accompany higher temperatures [30].

Adaptation of some current agrosystem practices may be a more sensible approach. Reorienting vineyard rows toward the east, with a N-S +20° or +30° deviation is suggested as a means to expose vines less to the warmer afternoon sun [91]; this might be feasible, and gradually accomplished over a few years period, as vineyard sections need to be replanted at Casa Castillo. It is entirely possible that even RF-covered vineyards at Casa Castillo and other Jumilla areas start suffering the results of harsher climate during the 21st century. Some type of RF manipulation or management may then be needed to lessen the severity of climate; although RF relocation or rearrangement is currently not economically feasible, it might become necessary to extend these RF covers to the lower parts of the estate, either with machinery or using hand labor. Improving the recycling and use of organic mulches, especially in areas between vine rows, could also help in minimizing evaporation and reducing soil erosion [91]. Non-pruned vine wood is usually removed at the end of a vineyard's life; in California vineyards, disking—a light form of soil tillage—of old vine and pruned wood returns much organic material to the soil as litter [91,113]. Modifying vine pruning practices to maintain a denser leaf canopy could also help to protect grape bunches from excessive insolation and heating.

A practical approach often advocated for some vineyard areas is to switch to grape varieties that better withstand warm and dry conditions [21,91,95]. There is considerable variation among *Vitis* grape species and cultivars regarding heat sensitivity; for example, photosynthetic ability in *Vitis aestivalis* leaves declines faster in hot conditions than in *Vitis vinifera*, which is more drought tolerant [76]. Grape varieties with long growth cycles and late maturation might be able to survive better; a change from white to red grapes—generally more heat resistant—has already happened in some German winegrowing areas, as a response to rising temperatures [95]. As climate becomes increasingly warmer, growers in cooler, more northerly climates than that of Murcia might switch to grapes best adapted to hotter environments, e.g., replace Chardonnay, Tempranillo, or Semillon for Garnacha, Zinfandel, or Carignane [76,95]. However, as noted above, this approach, would not work for areas where these types are already cultivated, such as Jumilla.

Much recent research has shown that grape varieties differ considerably in their physiological responses to drought and/or water stress. Isohydric plants maintain a constant midday leaf water-potential when water is abundant, as well as in dry periods, by reducing stomatal conductance to limit transpiration. Anisohydric plants have more variable leaf water-potential and keep their stomata open and photosynthetic rates high for longer periods, even in the presence of decreasing water availability; they apparently evolved in more arid regions than isohydric types [76,114,115].

Anisohydric grape species or cultivars (e.g., Merlot, Chardonnay, Syrah) are less susceptible to xylem cavitation during periods of water stress than isohydric types (e.g., Garnacha, Tempranillo). Cavitation occurs when the water column connecting the canopy to the roots is broken by spaces filled with air or water vapor, and the plant then suffers embolism [116]. By restricting stomatal water loss, isohydric plants limit carbon gain as well, thus grow more slowly than anisohydric cultivars; anisohydric vines also exhibit clear drought-avoidance strategies, developing deeper roots and a larger root/shoot ratio [76,114]. In general, the anisohydric strategy appears more beneficial for plant survival during prolonged drought periods, and also confers greater resistance to biotic stress, such as that caused by fungal infections [115]. As further detailed data about these plant strategies become available, viticulturalists should be able to select more adequate grape varieties; however, given current knowledge, it seems that anisohydric cultivars should perform better in warmer and drier areas.

A final obvious alternative to offset the effects of a warmer climate would be to introduce irrigation in formerly dry-farmed vineyards [91,95]. Asides from any possible issues concerning wine quality [76], this approach seems particularly ill-advised for Jumilla, as it would add further pressure to the already damaged regional aquifers. In the long run, it might also be a costly option. Owing to the great depth from which the groundwater is pumped, current extraction costs are ~15% of total agricultural costs [105]; with increasing overexploitation and regional competition for water, it seems likely prices would climb steadily throughout the 21st century. All things considered, the future of viticulture in Jumilla appears gloomy and uncertain.

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Conflict of interest

The author declares no conflicts of interest in this paper.

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