Land and water use management in vine growing by using geographic information systems in Castilla-La Mancha, Spain

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Abstract

Vine growing plays an important role in many semiarid farming regions all over the world, also as a permanent plant cover in terms of preventing erosion, sustainable use of land and water resources, defence against desertification and settling population in rural areas. This paper shows how to build up a Geographic Information System (GIS) on vine growing that could be a useful tool to support decision making processes related to land and water management in Castilla-La Mancha, the region of Spain with the largest area of vineyards, where wine growing and making are becoming competitive, even at the world scale. The System allows relating the environmental, social and economic effects of managing land and water use in this agricultural sector, to test feasible alternatives from a regional perspective and according to different stakeholder’s viewpoints. GIS appears as the only tool that can support the large database sets requested for such analysis.

Keywords: GIS; Grapevine growing; Land-use planning; Water management; Decision making

1. Introduction

Land-use changes in farming areas that derive from declining of agricultural practices or even from frequently unreasonable overexploitation of water resources have led many
semiarid regions of the world to boundary conditions demanding urgent strategies of water management towards sustainable development (Hugget, 1993; Brandt and Thornes, 1996). As human demands increase, the sustainability of land use is in question. Better land management involves identifying land-use changes, understanding current land-use patterns or features, and assessing economic and ecological benefits and costs that arise from land-use practices, as well as finding the best alternatives for each area (Wu et al., 2001). Water scarcity can bring about the impoverishment of the land and other natural resources caused by human activities and climate variation, particularly rainfall variability and evaporation (Pereira et al., 2002). However, our capabilities for analysing such land management has been traditionally limited for two reasons: the difficulty in acquiring useful information over vast areas and the lack of a means to effectively process and analyze the acquired data. Because of the many factors associated with each feature under study, analysis and manipulation using manual methods are too costly, too time-consuming, or practically impossible (Aronoff, 1989). Iacovides (2001) states that there is a need for well thought out and technologically advanced information systems for integrated water resources management and for coping with water scarcity.

Farming schemes in many semiarid regions of the world have been implemented to cope with water scarcity by approaching appropriate land and water technologies and management skills. Agriculture in the Mediterranean Basin has always been highly dependent on the traditional trilogy of rainfed crops, which is cereal–vine–olive, resulting in a close relationship with the environment that overcomes local, regional and national borders. Improper management of dry-farming systems under these conditions would lead to break the existing balances resources demand and supply, enhance erosion and land degradation, waste rainfall resources and give rise to rural depopulation.

The relevance of growing grapevines under semiarid conditions was universally accepted as a farming alternative in those regions of the world where wine making is more than an industrial activity. On a global scale, Europe has 55% of the world surface grown with vines, and the region of Castilla-La Mancha, Spain, with more than 0.5 million ha shows the higher rate of vine growing area in the world (8% of the world vine surface and 10% of the grape production) (Salinas et al., 1996). The soils where grapevines have been traditionally grown are not quite deep, have little water retention capacity and there are few agricultural alternatives to grow any crop else. The aim of the farmer was to produce grapes in quantity, regardless its quality and market price. Irrigation of vineyards was not permitted in Spain until 1996, when many dry-land grape vine growers have moved from their traditional farming systems to irrigation systems. There is a need to provide some support and encouragement to vine growers to manage irrigation practices to reduced demand systems and technologies.

The global markets are also forcing changes in viticulture. The grape and wine quality is highly dependent on the concept of terroir and with it the variety–rootstock combination. This may be described in broad terms as the combination of climate, topography and soils (Van Graan, 2002). It becomes necessary to know the requirements of each particular variety and rootstock combinations along with the best geographical situation, available technology, environmental conditions and social aspects to achieve the optimum productive results. The aim is to produce distinctive wines that reflect the characteristics of the land.
Besides, vine growing plays an important role not only from the economic point of view, but also environmentally as a permanent plant cover in terms of preventing erosion, managing land and water resources in a sustainable way, defending against desertification and settling population in rural areas (Martín de Santa Olalla, 1994). In this way, the reformation of the European Union’s agricultural market organisation established a special subsidy for vineyards grown under extreme farming conditions, called “heroic vineyard”, due to its impact on population and environment (CERVIM, 2001).

Many variables affect the growth of grapes, some according to place, and some by time. For each factor, there is information, much of it specific to the location of the vineyard. The development of information technologies in agriculture are currently allowing a broad band of capabilities related to collecting and analysing data from crop growing and its yielding factors spatially involved (Harvell, 1996). Geographic Information Systems (GIS) provide easy and consistent access to natural resource data and thus should be considered as very useful tools to integrate information coming from different sources, which makes it very efficient for viticulture land-use planning and management (Lang, 1996).

Solutions to most landscape-scale problems require access to comprehensive spatial databases describing natural, cultural and economic resources, that are often unavailable or of questionable reliability. Coupling of GIS with process and assessment models and graphical user interfaces results in a variety of decision support tools which integrate and organize information necessary to make timely and informed decisions with consistent recommendations based on document decision criteria (Johannsen et al., 2000).

GIS can be used effectively to assess vine-growing decisions, which are only as good as the information available. Information on the vineyards can be analysed and correlated by spatial reference (Gordon, 1997; Smith and Whigham, 1999; Tamaluddin and Kamaruzaman, 1999).

This paper describes the results achieved in a research project to provide guidelines for the global restructuring of the grape vine growing and wine making sector, by focussing on land-use management concepts from the three viewpoints of vine growers, wine makers and decision makers by using GIS tools. The specific objectives were to start out with a vine growing information system in a regional scale, identifying land-use changes, then to identify vineyard areas with low annual amounts of water available from rainfall where irrigation support might be strongly recommended, and finally evaluate the effects of water scarcity in grapevine growing on regional land-use patterns so as to analyse feasible water and land-use management alternatives.

2. Material and methods

2.1. Description of the study area

Castilla-La Mancha (Fig. 1) is a large region of Spain with an area of 79,225 km² placed at a plateau of an altitude averaging between 600 and 800 m, which occupies the southern centre of Spain. This tableland is surrounded by the Central range in the north, the Iberian range in the north-east and the Sierra Morena in the south. Several rivers flow through the flatlands, from the east to the west, Guadiana and Tagus, and from the north to the east, Jucar and Segura. This geographical situation impedes the penetration of the warm air...
streams blowing from the Mediterranean Sea, transforming the climate of this region into continental, with low annual rainfall (<450 mm), an average 2500 h of sunlight per year, dry and hot summers (25 °C average in July) and cold winters (3.5 °C average in January).

Castilla-La Mancha has a population of 1.75 million, with low density (22 person/km²) and high dispersion (55% of all the 504 counties are below 500 people). Farming is still the main way of life in this region and the driving force for its development. Vineyards occupy the second place in crop area (21% of the total crop area), after cereals (49%) and before olive groves (11%). Grapevine growing and wine making in Castilla-La Mancha represent more than 21% of the final agrarian production (Castillo et al., 2003).

Most vineyards are grown without irrigation. Under these conditions the branching habit of vine stocks is creeping, the farmer tends to plant not more than 1500 plants/ha, the vineyards have small size (less than 4 ha), and the regime of tenancy is usually own property (Montero et al., 1999). There is a great diversity concerning to the use of plant material, although the varieties that are being well demanded by markets are still in disadvantage with regard to the classical varieties. Recent plans of restructuring and improvement of vineyards lead to change of varieties grown (Garcia Martin, 2003). The classical varieties such as Airen, Bobal, Monastrell, decrease whilst other varieties typical from other vine regions increase (Tempranillo, Syrah, Cabernet Sauvignon and Merlot).

On a global scale, Castilla-La Mancha is the region with the higher rate of vine growing area in the world, with more than 0.55 million ha, 8% of the world grape vine area, whilst the yields are much lower than the European average (Castillo et al., 2003). Therefore, it is broadly assumed that vineyards and wine making are essential components of the regional development and its projection for the future is ever-increasing abroad, especially due to the effects of its production over the regional and international markets.
2.2. GIS related layers

A GIS was set up, particularly focusing on those areas where larger changes in land use related to vineyard are sensed and where those changes involve a higher use of water resources or environmental deterioration (Fig. 2). For such a purpose, the ArcGIS (ESRI, Redlands, California, USA) software was used because of its capabilities to visualise, explore, look up and analyse spatial information. The maps were projected to the Universal Transverse Mercator (UTM) coordinate system zone 30 north.

First actions consisted of the preliminary diagnosis of the current situation in the most important vineyard areas, evaluating the influence on both the qualitative and quantitative size estimation. Special attention was paid to necessary infrastructures, farming area distribution, crop yields, weather parameters, geomorphology, land use, hydrology, and social and economic indicators. The system was laid for implementing a monitoring programme through the analysis of the distribution, production and outcome of time rates related to agronomy, economy and social affairs (Merenlender, 2000; Heaton and Merenlender, 2000).

Information on geography, roads and other infrastructures and hydrography was derived from the digital raw data, scale 1:200,000 provided by the Spanish Centre of Geographical Information. The same source was used to process the elevation layers, slope and aspect, from a 100-m equidistant elevation contour map, scale 1:1,000,000. The soils were consulted from the soil survey of the Spanish Soil Information System SEIS (De la Rosa and van Diepen, 2002), following the Soil Taxonomy Classification (USDA, 1987). Fig. 3 represents the maps of slopes and soils, showing the relative homogeneity of slope values, according to the physiographical characteristics of the region above described. Inceptisols are predominant and account for 74.6% of the region area. Alfisols rank second with 13.0% and the other soil orders, Aridisols and Entisols, cover 6.3 and 6.0%, respectively.

The land cover layers were compiled from the combination of two sources of information. Firstly, the Corine land cover is a key database that provides a pan-European inventory of biophysical land cover applied to integrated environmental assessment, using
a 44-class nomenclature. It is made available on a 250 m × 250 m grid database, which has been aggregated from the original vector data at 1:100,000 (Bossard et al., 2000). Secondly, the agriculture census provided by the regional government of Castilla-La Mancha corrects and improves the crop distribution and gives support to other technical and agronomic studies focusing at the local scale.

2.3. Spatial distribution of vineyards according to annual rainfall

The next step was to identify vineyard fields in those areas presenting the highest density of vine growing, pointing out the problems with water resources availability. Rainfall water resources were then analysed by studying the spatial distribution of rainfall all over Castilla-La Mancha and its incidence on farming practices in vineyards derived from the particular situation of vineyards that are adapted to rainfed conditions below 500 mm/year. To create rainfall layers, we used monthly precipitation data from 372 weather stations property of the Spanish Institute of Meteorology and also of the Government of Castilla-La Mancha, located within the boundaries of the region and also in border areas. Although the time series varies, only those stations with data of a number of years ranging between 10 and 36 were considered. The analysis of the homogeneity of data series relied upon the procedures indicated by Allen et al. (1998). The objective was to assign the local estimation of weather parameters derived from real observations and therefore interpolate to other locations within the study area. The methodology applied based on a general purpose interpolation tension spline method, which fits a minimum-curvature surface through the input points, by using a polynomial function (ESRI, 1996). It fits a specified number of 12 nearest input points, while passing through the sample points.

3. Results and discussion

A Geographic Information System basing on grapevine growing features was designed at a regional level, with the main aim of supporting decision making on land-use planning and management related to Castilla-La Mancha’s viticulture. Agronomy information on
vine growing in Castilla-La Mancha was also introduced into the GIS, as well as the census of viticulture, population and economy.

Once the GIS is operational, it could be observed that the most important farming areas growing grapevines are located in the central part of Castilla-La Mancha, where the soils are mainly calcixerollic or petrocalcic xerochrepts (Fig. 3), which are stony in the surface, with medium texture, low capacity to retain water and shallow root zone (<50 cm), which make it difficult to grow any herbaceous crop during the summer season without irrigation. Vine growers increase spacing of plants under rainfed conditions to increase the ground area per plant, when possible break through the impervious petrocalcic layer at the moment of plantation to enhance the roots to explore deeper zones, and apply other local tillage practices to limit soil evaporation. Canopy manipulation is also relevant since ET is influenced by changes in leaf layers and canopy dimension due to light intensity, humidity, leaf temperature, air flow and also evaporation from the soil surface (Smart and Coombe, 1983).

Besides, groundwater resources are depleting and irrigation is significantly restricted to certain areas and duties. Although irrigating vineyards is now becoming more and more important, most vineyards are still grown under rainfed conditions, since irrigation was not permitted until 1997. Irrigated vineyards were then identified and quantified its area, resulting in 12.3% of the whole grapevine area (Table 1). The irrigation systems are mostly drippers, with efficiencies overcoming 90% (Tarjuelo, 1999). In Castilla-La Mancha, grapevine water requirements are considered to be above 350 mm on average along its vegetative period, from April to September, which makes irrigation duties range between 100 and 200 mm/year (Sotes, 2001). The water use efficiency (WUE, amount of crop produced per unit of irrigation water applied, kg/m³) reaches 5.4 for average yields of 8 t/ha, whilst traditional arable irrigated crops such as barley or maize scantily reach 3.5 and 1.8, respectively, for optimal yields in Castilla-La Mancha (Lopez Fuster and Montoro, 2003).

The consequences of supplying water through irrigation or from rainfall at a level, which is less than optimal, will result in the activation of various water deficit response mechanisms, such as stomatal closure that can lead to a decrease in transpiration and an increase in transpiration efficiency, that is, dry matter produced per unit of water transpired (Winkler et al., 1974). Irrigation water may be a legitimate crop water use management strategy in Castilla-La Mancha and this is embodied in techniques such as regulated deficit irrigation (RDI) and partial rootzone drying (PRD). RDI consists of applying a short duration of water stress, immediately after berry set in order to control berry size and vegetative growth. The practice of simply irrigating at less than the full vineyard water requirement for the entire growing season is not considered to be RDI (Dry et al., 2001). But if part of the grapevine

<table>
<thead>
<tr>
<th>Year</th>
<th>Rainfed (ha)</th>
<th>(%)</th>
<th>Irrigated (ha)</th>
<th>(%)</th>
<th>Total (ha)</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>547,266</td>
<td>93.9</td>
<td>35,931</td>
<td>6.1</td>
<td>583,197</td>
<td>100</td>
</tr>
<tr>
<td>2001</td>
<td>524,184</td>
<td>88.8</td>
<td>66,032</td>
<td>11.2</td>
<td>590,216</td>
<td>100</td>
</tr>
<tr>
<td>2003</td>
<td>512,870</td>
<td>87.4</td>
<td>73,585</td>
<td>12.6</td>
<td>586,455</td>
<td>100</td>
</tr>
</tbody>
</table>

root system was slightly dried and the remaining roots kept well watered, chemical signals produced in the drying roots reduced stomatal aperture, providing the plant with the potential to regulate not only growth but also to increase water use efficiency and fruit quality (Loveys et al., 2000).

Other crop water use management strategies must be focused on rainfed vineyards, which represent 87.4% of the total grapevine grown area. A spatial distribution pattern of vineyards was represented to analyse the performance of grapevine plants according to different situations of water availability, and thus foreseeing several agronomic solutions in the short term and taking into account the land-use change tendency during past years and the international repercussion on the world markets. Fig. 4 shows the spatial distribution of annual rainfall in Castilla-La Mancha, observing that in the central part of the region, where most grapevine growing areas are located, the rainfall is below 450 mm/year. It can be applied to the assessment of high-quality yield vineyards, changing scenarios to minimise water consumption or to maximise yield with a known water amount. Versatile application can be achieved by integrating different crop models into the GIS making it easy to determine appropriate study areas according to the scenarios proposed (Hartkamp et al., 1999; Qing and Linvill, 2002). The GIS is designed as a baseline for viticulture zone characterization to express the relationships between population, agri-environmental and economic effects of possible actions carried out in the field of Castilla-La Mancha’s viticulture, facing feasible solutions from a global perspective as a reference framework for stakeholders.

Vineyards in Castilla-La Mancha as in other Mediterranean regions have resulted to be more than not only a productive agricultural activity, but also a key factor in fixing rural population (Montero and Brasa, 1998). Those counties where there is no grapevine growing areas have an average population density below 19 people/km²; in those with a vine area ratio up to 30% of the farming area, the average population density is 21 people/km²; in those where vineyards represent above 30% of the farming area, the average population density reaches 38 people/km².

As a result of the global analysis of the distribution of European Union’s Common Agriculture Policy subsidies allocated in 2001 to the farmers in Castilla-La Mancha, we could clearly observe that those counties with larger vine area ratio (above 30% of the farming area) received a total amount of subsidies over €2.75 M, whilst those with no vines
scarcely reached €0.27 M. Taking into account that grapevine growing is not granted with any subsidy, we should conclude that viticulture and wine making have synergic actions on the rest of the agricultural activities, promoting agrarian employment in associated sectors, raising the farmer incomes and thus fixing the population to the rural areas.

As for the water resources availability, the spatial and seasonal rainfall distribution was studied in order to analyse the relationships between rainfed grapevine growing surface areas and precipitation intervals in all the counties of Castilla-La Mancha. Fig. 5 shows the areas grown with grapevines within municipalities under the different ranges of annual rainfall considered. It can be noted that most vineyards of Castilla-La Mancha are grown under environmental conditions of shortage, between 350 and 450 mm/year. It can be noted that 72% of the land growing vines is located in geographical areas where the average rainfall ranges from 350 to 450 mm/year. When studying the trends in rainfall distribution along the year, following the phaenological stages as described by Baillod and Baggiolini (1993), small differences can be observed depending on the rainfall interval which the territory is included, mainly due to the winter rains. In a more detailed analysis, Fig. 6 shows the spatial distribution pattern of cumulated rainfall in each phenological stage of grapevine growing as compared to the pattern of annual precipitation. Although the stage of winter dormancy presents 48% of the annual rainfall, 29% from shoot to bloom, 17% from bloom to grape veraison and 6% from veraison to harvest, there are just slight differences in the regional distribution pattern. The grapevine plants have structural

![Fig. 5. Spatial distribution of grapevine growing area over the counties of Castilla-La Mancha according to six different rainfall intervals.](image-url)
difficulties to grow and develop under rainfed conditions with no water supplied by irrigation (De Juan et al., 1998), but the rainfall cumulated during the winter period is considered a reserve that the grapevine plant will use during its vegetative cycle. The adaptation of vines to very dry environmental conditions depends more on its capability to deep rooting than its resistance to low soil water potential values (Williams and Mathews, 1990). Montero et al. (1999) confirmed the good performance of the grapevine root system development planted on soils with a petrocalcic layer. This makes grapevine growing to be considered as one of the few cropping choices able to capitalize the hard environmental conditions of semiarid regions under these conditions.

The negative effects of water scarcity are enhanced by the type of soil in which most vineyards are grown. The soil can be considered a reservoir that operates as a buffer of water availability, especially during those summer periods of maximum evaporation. Vineyards planted on soils with more water retention capacity have a more steady regime of quality production and those with poorest characteristics offer few alternatives for other crops that could be grown under profitable dry-farming.
Table 2
Distribution of monthly rainfall according to different intervals of annual rainfall (mm/year) and grapevine growing area affected, having into account the phenological stages

<table>
<thead>
<tr>
<th>Phenology</th>
<th>Harvest-soot</th>
<th>Shoot-bloom</th>
<th>Bloom-veraison</th>
<th>Veraison-harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of rainfall (mm/year)</td>
<td>Area (ha)</td>
<td>September</td>
<td>October</td>
<td>November</td>
</tr>
<tr>
<td>250-300</td>
<td>11,036</td>
<td>24</td>
<td>41</td>
<td>32</td>
</tr>
<tr>
<td>301-350</td>
<td>41,375</td>
<td>26</td>
<td>41</td>
<td>35</td>
</tr>
<tr>
<td>351-400</td>
<td>166,299</td>
<td>30</td>
<td>45</td>
<td>47</td>
</tr>
<tr>
<td>401-450</td>
<td>257,737</td>
<td>29</td>
<td>42</td>
<td>41</td>
</tr>
<tr>
<td>451-500</td>
<td>74,721</td>
<td>29</td>
<td>45</td>
<td>48</td>
</tr>
<tr>
<td>&gt;500</td>
<td>38,502</td>
<td>39</td>
<td>68</td>
<td>87</td>
</tr>
</tbody>
</table>
conditions; in this case, RDI appears to be a good solution when appropriate management criteria are applied, increasing from two to four times the profitability of the vineyard (De Juan et al., 1998). Grapevine water requirements are above 350 mm on average, divided into 2% in winter dormancy, 10% from shoot to bloom, 43% from bloom to grape veraison and 45% from veraison to leaf fall (Hidalgo, 2002).

Table 2 shows the average values of monthly rainfall for the six intervals in which vineyards can be divided according to available rainfall. It provides with information needed to assess real water supply demanded by vines in each phaeological period in a regional scale, showing that grapevines are perfectly able to survive under the hard conditions prevailing in most areas of Castilla-La Mancha, although improving quality and quantity yields will depend upon local farming practices and irrigation water supply.

4. Conclusions

Castilla-La Mancha is the region with higher concentration of grapevine area all over the world. It is a territory where traditional viticulture is well adapted to the environment, not only from a physical point of view, but also according to human activities. Nevertheless, because of the vast territory studied, further research focusing on a local scale is requested towards the set up of a zoning scheme as a key element in the decision support system of viticulture. Basing on these results, grapevine areas could be ranged according to physiography, farming capability and vine variety, and provided that all requirements are met, an irrigation scheduling model could be thus proposed fitted to the different situations.

Almost three-quarters of the vine growing area of Castilla-La Mancha are subject to annual rainfall limitations, which together with other natural constrictions, make it highly recommended to apply support irrigation technologies that would help the farmer to get better quality yields, provided that there is a regional balance between quantity and quality. New trends in viticulture result in better wine making that can afford the best world markets. Grapevine growing appears as a good land use alternative, which is demanding new ways to assist decision makers in giving guidelines to allocate water resources from other more consumptive uses. GIS is the only tool that can support the large database sets requested in such analysis.

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