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# Long-term implications of water erosion in olive-growing areas in southern Spain arising from a model-based integrated assessment at hillside scale

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ABSTRACT

In this paper, a model-based integrated assessment of the long-term consequences of water erosion in four olive groves with different conditions in Andalusia (southern Spain) is carried out. The assessment is based on a system dynamics model built at hillside scale. The modelling approach tackles common difficulties arising from the relative scarcity of data and the uncertainty of the long term. On the one hand, model results have allowed characterising the nonlinear dynamics of water erosion. On the other, they have showed that positive gross margins may definitively vanish after around 100 years in some olive-growing areas. In spite of this, the adoption by farmers of soil conservation practices is limited. The assessment shows that the loss of yields due to the erosion-caused reduction in soil water availability lead to annual economic losses ranging between 1 and 2.8 € $ha^{-1}$ $yr^{-1}$ in the studied rainfed orchards. These losses are completely obscured by the normal fluctuations in economic and production variables, so that they do not give farmers adequate warning of the consequences of non-sustainable soil management.



## 1. Introduction and purposes

Olive is one of the major crops in the Mediterranean basin, concentrating the production of 95% of the world olive oil (FAOSTAT, 2010). This importance is paramount in Spain, where there is about 51% of the olive-growing area of the European Union (European Commission, 2012). Particularly, Andalusia (southern Spain) is the largest olive growing region in the world with 1.5 Mha, roughly 20% of its total area (CAP, 2010).

Historically, olive groves have occupied hilly areas of shallow soil, where many other crops do not develop or produce poor yields. Although intensive-cultivation systems and new plantations in good soils have thrived in Andalusia in recent decades, olive groves on steep slopes and under rainfed conditions are still common. Several authors, such as Beaufoy (2001), Gómez (2009) and Gómez-Limón et al. (2012), have pointed out that one of the main negative environmental impacts associated to this type of olive cultivation is soil erosion. And indeed, the occurrence of high rates of erosion in olive-growing areas in southern Spain has been reported for decades (e.g. Bennett, 1960).

Under Mediterranean climate conditions, the function of the soil as water storage during the dry season is of critical importance and is usually a major limiting factor for olive yield (Henderson, 1979; Gómez et al., 2008). It is apparent that, if erosion is not prevented, this function will disappear or be severely damaged at some point, thereby entailing the collapse of the entire system. Nevertheless, the adoption by farmers of soil conservation practices is limited in these areas and, at best, such practices have had a moderate effect in reducing erosion rates to tolerable levels (Gómez, 2009).

Farmers justify their attitude as follows. Most of the orchards on steep slopes, established without terraces before the advent of farm mechanisation in the region, have tree lines following the direction of the steepest slope. Under this conditions contour ploughing is unfeasible. Indeed, in those orchards on the steepest slopes (36% of the olive-growing area has gradients greater than 15%, of which 12% has gradients greater than 25%) the risk of overturning the tractor is considerable. On the other hand, farmers point out that cover crops, the alternative erosion control

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technique, complicates soil management because, under rainfed conditions, crops must be killed (chemically or mechanically) in late winter or early spring to avoid competition with olive trees for soil water (Gómez, 2005). They also argue that varying conditions makes it uncertain what the optimum dates to control cover crops are, and that there is a potential risk of yield losses if they are improperly managed (Gómez and Giráldez, 2010). In addition, most erosion control measures have negative financial and economic returns, as noted for UK conditions by Posthumus et al. (2013). As a result, soil conservation practices have been mainly enforced by regulations of the Common Agricultural Policy to date.

Changing these attitudes is not a straightforward task. Some reaction could be expected if farmers perceived the consequences of non-sustainable soil management. However, since the loss of soil productivity is steady, it is obscured to them by the normal variability of economic and production variables and by changes in farm management. As an illustration, Vanwalleghem et al. (2011) evaluated historical erosion rates and olive yields in a mountainous area in southern Spain since the late 18th century. They used a combination of archival research, field survey and model analysis. Their results indicated high erosion rates resulting in the loss of approximately 450 mm of the original soil profile, of which 900 mm remain to date. However, olive yield increased during that period from 500 to 2500 kg ha$^{-1}$ due to the adoption of improved agricultural technologies.

Therefore, there is a need of increasing the level of information of stakeholders, especially farmers, about the long-term implications of the current rates of erosion. But this goal presents the challenge of getting a better understanding of the dynamics of the degradation process and their interaction with key variables such as olive yield.

A growing number of published studies report the results of measurements of soil erosion rates at hillside and catchment scale on olive groves under different soil management techniques (e.g. Gómez et al., 2008; Taguas et al., 2011). However, these studies cover a limited number of years and are not concerned with the long-term implications of the problem. Certainly, field experiments allow describing the present state of an agricultural system, but can hardly determine any inflection point in the future. For this purpose, some formal representation of the processes of land degradation is necessary. In fact, models have already been used to study the impact of soil erosion on crop productivity (Lal, 1987).

Aware of this, the Spanish National Action Programme to combat Desertification (MAGRAMA, 2008), which includes olive groves among the vulnerable socio-ecological systems threatened by land degradation, has adopted an assessment methodology based on multidisciplinary models of representative areas (Ibáñez et al., 2014). These are special developments of a single theoretical model conceived to carry out long-term assessments of overexploitation of natural resources (Ibañez et al., 2008a), which has proved to be useful for a variety of land uses (Ibáñez et al., 2008b, 2012; Martínez Valderrama et al., 2011).

One of the models used in the Programme is focussed on degradation by water erosion in areas covered by woody crops. In the present work, this model is referred to olive groves and used to estimate: (i) the risks of losing different amounts of soil before a given number of years and (ii) how long it will take for gross margins to permanently fall below zero due to the loss of soil productivity as a result of the erosion-caused reduction in soil water storage capacity. These estimates are thought to be the most relevant information to be reported to stakeholders. In addition, the model allows understanding the long-term dynamics of water erosion and the interplay among different variables.

Four case studies are evaluated. They are olive groves representative of some of the main types existing in Andalusia, which were studied in previous model-based hydrologic analysis (e.g. Abazi et al., 2012). These case studies are placed in the municipalities of Córdoba, Obejo (Córdoba), Aznalcázar (Sevilla) and Iznalloz (Granada), so that they are hereafter referred to as COR, OBJ, AZN and IZN, respectively.

## 2. Modelling approach

The model used in this work is an integrated assessment model since it integrates multidisciplinary processes into a single framework aimed at generating useful information for decision-making (Jakeman and Letcher, 2003). The need for this type of models to enhance the effectiveness of decision-making and management has been widely acknowledged (Kelly et al., 2013).

Building an integrated assessment model to evaluate the long-term implications of water erosion in olive-growing areas presents important difficulties. Regarding calibration, time-series data on the endogenous variables are normally non-existent or too short for specific sites. Therefore, the model cannot be calibrated to reproduce historical observations. Also, data samples are usually not enough or unsuitable to estimate relevant relationships by means of regression analysis. Regarding validation, the scarcity of data precludes assessing model performance by means of quantitative tools, such as those reviewed by Bennett et al. (2013). In any case, historical observations are bounded to be insufficient to validate a model whose purpose is to explore states of degradation never observed before in the site.

These difficulties have been dealt with in the following way:

(i) The model follows the system dynamics approach, which is especially recommended when facing the aforesaid difficulties (Forrester, 1961; Sterman, 2000). A system dynamics model consists in a system of ordinary differential equations that makes a stock-and-flow representation of the studied system.

(ii) As required by the system dynamics approach, all the model parameters have a real world counterpart, except the '*m*-parameter of Thornes's erosion model' (Table 1). To run the model, all these parameters must take values that are representative of the study area. Using meaningful parameters greatly facilitates model calibration because it makes possible to obtain their representative values from the literature or expert opinion, if they cannot be estimated from *in situ* data. It also makes the model much more understandable than other comparable models (e.g. Nelson et al., 1998).

(iii) The model includes theoretical, well-behaved functions that are calibrated to a particular case study simply by means of a few representative parameter values. As a result, these values ultimately determine the rates at which the processes represented in the model evolve over time. See Section 3.5 for details.

(iv) A qualitative validation of the model was carried out by thoroughly following the specifications laid down by the system dynamics approach (Sterman, 2000). Thus, the model was tested on: (a) its suitability to the purposes of the assessment (see Section 5); (b) its conformance to fundamental formulation principles, e.g. variables are adequately bounded by model structure, not in an *ad hoc* basis; (c) its robustness in facing extreme variations in input conditions (by running exploratory simulations); and (d) its coherence and plausibility (point v).

(v) The complete set of representative parameter values specifies the present or initial state of the modelled olive grove. Model structure is globally coherent and plausible in the sense that its stochastic output will always be consistent