Universidad de Granada

Departamento de Edafología y Química Agrícola

Impacto medioambiental del cultivo de especies subtropicales en terrenos con fuertes pendientes en la costa de Granada. Medidas correctoras.

Tesis Doctoral

Carmen Rocío Rodríguez Pleguezuelo

Directores: Dr. Víctor Hugo Durán Zuazo
Dr. Francisco José Martín Peinado

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IMPACTO MEDIOAMBIENTAL DEL CULTIVO DE ESPECIES SUBTROPICALES EN TERRENOS CON FUERTES PENDIENTES EN LA COSTA DE GRANADA. MEDIDAS CORRECTORAS.

Memoria presentada por la doctoranda Carmen Rocío Rodríguez Pleguezuelo, para aspirar al grado de Doctor en Ciencias Ambientales por la Universidad de Granada

Carmen Rocío Rodríguez Pleguezuelo

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Fdo. Francisco José Martín Peinado

Fdo. Víctor Hugo Durán Zuazo

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Resumen

Esta tesis tiene cinco capítulos, en los que se expone la problemática del cultivo de especies subtropicales en terrenos con fuertes pendientes desde diferentes puntos de vista. En el capítulo I se realiza un análisis detallado de los cambios en el uso del suelo en una cuenca representativa de la zona de estudio, haciendo especial hincapié en las fuerzas socio-economicas que los impulsan. Se estudia también, en el capítulo II, el efecto de distintas cubiertas de plantas aromaticas y de la vegetación espontanea sobre el control de la erosion y la escorrentía en comparación con el suelo desnudo, así como el transporte de metales pesados y pérdidas de carbono orgánico. Asímismo, utilizando la técnica de las bolsas de hojarasca, se estudiaron las tasas de descomposición de ésta y el reciclado de nitrógeno comparando dos escenarios de agroecosistemas diferentes: el no alterado, que consitió en una mezcla de plantas herbáceas y matorrales leñosos; y el alterado, de cultivos subtropicales en terrazas de cultivo con cubiertas de plantas aromaticas en los taludes (Capítulo III). Se llevó a cabo también un estudio para determinar el riesgo potencial de contaminación por nutrientes en mango (*Mangifera indica* L. cv. Osteen) y chirimoyo (*Annona cherimola* Mill. cv. Fino de Jete) utilizando para ello lisímetros de drenaje, que también se emplearon para establecer un balance de nutrientes. Los resultados se muestran en el capítulo IV. En el último capitulo de esta tesis (V) se estudian los efectos de distintas dosis de riego en mango sobre la producción de fruta, tamaño de frutos, parámetros de calidad y macro- y micronutrientes en hoja y frutos. Las metodologías aplicadas durante la ejecución del trabajo de campo y laboratorio para el desarrollo de esta tesis son presentadas en cada uno de los capítulos, asi como los resultados obtenidos. Finalmente, se muestran las conclusiones generales al final de esta memoria.

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Summary

This thesis has five chapters, providing a general introduction to the problems originated by subtropical crops cultivated on steep sloping terrain along the coast of Granada. In Chapter I, land-use changes from 1978 to 2007 in a selected representative watershed of the study area are analysed, focusing particularly on the influence of socio-economic driving forces. In Chapter II, different aromatic plant covers and native spontaneous vegetation were applied to determine the effectiveness of the covers in reducing soil erosion, runoff, and potential pollution risk by agricultural nutrients and heavy metals in comparison to a control of bare soil. Using a litter-bag technique, we assessed the decomposition rates and N release in various types of litter, comparing two different agroecosystem scenarios: an unaltered slope consisting mainly of a mixture of herbaceous plants among spontaneous perennial woody shrubs and the altered slope cultivated with subtropical trees on terraces with groundcover plantings of aromatic, medicinal, and mellipherous plants (Chapter III). An experiment was conducted using drainage lysimeters to determine the potential risk of nutrient pollution in mango (*Mangifera indica* L. cv. Osteen) and cherimoya (*Annona cherimola* Mill. cv. Fino de Jete) orchards. These lysimeters were used to estimate the nutrient budgeting for each crop. The results are presented in Chapter IV. In the last chapter of this thesis (V), different irrigation treatments were applied to study the response of fruit yield, fruit size, quality parameters, and macro- and micronutrients in leaves and fruits. The methodologies applied during the field and laboratory work are presented for each chapter, together with the results. General conclusions are drawn at the end of the thesis.

Introducción

Las relaciones hombre-medioambiente han llegado a componer una lucha frente a frente que requiere de una nueva mentalidad conservacionista sobre todo en lo relacionado con la agricultura. Las actividades agrícolas influyen profundamente en el medioambiente al modificar los hábitats naturales y afectar a los paisajes, las plantas y los animales. En consecuencia, se requiere proporcionar una extrema importancia a la práctica de una agricultura sostenible y respetuosa del medio natural. En este contexto, las futuras actuaciones y adaptación de sistemas agrícolas tradicionales tendrán por objeto limitar cualquier contaminación de origen agrícola, fomentar el desarrollo de la producción, conservación de los recursos agua y suelo y mantenimiento la diversidad biológica.

El objetivo de la presente tesis fue el estudio del impacto medioambiental de la presencia de especies frutales de origen subtropical en terrazas de cultivo del sudeste peninsular español. Se evalúa el impacto de la construcción de terrazas de cultivo y posterior instauración de una agricultura intensiva de regadío y su efecto en la degradación física, química y biológica de los suelos y sus implicaciones en la calidad de las aguas superficiales y subterráneas del entorno. Paralelamente, se proponen las medidas correctoras para mitigar el efecto negativo de la agricultura tradicional y productivista, especialmente orientados a la conservación y uso sostenible de los recursos naturales agua y suelo. Y finalmente se proporciona una serie de información obtenida por medio de diversos ensayos en campo para optimizar la producción de cultivos subtropicales en terrazas y fomentar la agricultura sostenible de los mismos en este entorno montañoso tan frágil.

Los cambios en el uso del suelo (CUS) juegan un papel muy importante en los fenómenos actuales de cambio global. A escala planetaria, están directamente relacionados con los procesos de urbanización, migraciones, erosión y escorrentía, biodiversidad,…etc (Fu et al., 1994). A través de los siglos, los cambios de uso de suelo han trasformado los ecosistemas de la cuenca mediterránea, siendo ésta sometida a factores de diversa índole (socio-políticos, económica, e incluso culturales y religiosos) (Margaris et al., 1996).

En la costa de Granada y en particular en la zona de Almuñécar, estos CUS se han visto representados por la introducción de una agricultura intensiva de regadío basada en cultivos tropicales y subtropicales, entre ellos el aguacate (*Persea americana* Mill.), mango (*Mangifera indica* L.), chirimoyo (*Annona cherimola* Mill.), litchi (*Litchi chinensis* Sonn.) y otros (Foto 1). En los paisajes agrícolas tradicionales de montaña el empleo de productos de síntesis en el proceso de producción era mínimo y los cultivos se establecían en laderas y terrazas de construcción manual. Actualmente, estas estructuras manuales han sido sustituidas por otras terrazas de mayor tamaño hechas con maquinaria pesada y que ocasiona un gran impacto paisajístico. El aterrazado, es una técnica agraria utilizada para recoger agua y reducir la erosión, haciendo útiles desde el punto de vista agrario determinados terrenos que de otra forma no lo serían (Foto 1). Las terrazas han transformado los agroecosistemas mediterráneos desde hace siglos, así como en muchos lugares del mundo (Hillel, 1991; Treacy y Denevan, 1994; Beach y Dunning, 1995; Gardner y Gerrard, 2003).

En el Capítulo I de este trabajo se presenta un análisis detallado de los CUS desde 1978 a 2007 en una cuenca piloto del área de estudio, evaluando la influencia que los cambios socio-económicos promueven sobre los CUS.

Por otro lado, la eliminación de la vegetación es la principal causa de degradación del suelo y de la pérdida de su capacidad para disminuir los fenómenos erosivos. La relación entre erosión y vegetación es resultado de varios procesos complejos que actúan a diversas escalas de tiempo y espacio (Coppin y Richards, 1990; Morgan, 1986). A corto plazo, la vegetación influye en la erosión sobre todo por medio de la interceptación de lluvia y la protección de la superficie del suelo frente al impacto de las gotas de lluvia. A largo plazo, la vegetación influye en los flujos de agua y sedimentos ya que aumenta la estabilidad de los agregados de suelo y su cohesión y mejora la infiltración del agua en el suelo (Bochet et al., 2006; Durán y Rodríguez, 2008). Otro factor decisivo es el clima de la zona. El clima Mediterráneo se caracteriza por la alta variabilidad pluviométrica interanual con eventos de lluvia de intensidad muy alta. Así, Vallejo et al. (2005) clasifican muchas zonas de España como muy amenazadas por la erosión dentro del contexto europeo. Concretamente, en España, más de 22 millones de hectáreas (43,8% del territorio) están afectadas por tasas de erosión superiores a 12 Mg ha^{-1} año^{-1}, superando el límite tolerable de formación del suelo (Rojo, 1990). Además, en 2006, el 12,6% del territorio estaba afectado por tasas de erosión mayores de 50 Mg ha^{-1} año^{-1}, y el 34,1% registró tasas de 10 a 50 Mg ha^{-1} año^{-1} (DGB MMA, 2008). En concreto en la zona de estudio, los agricultores, tienden a mantener el suelo desnudo, desprovisto de vegetación, tanto de la plataforma, como de los taludes de las terrazas para facilitar las labores de recolección de la fruta, quedando las terrazas expuestas a un mayor riesgo erosivo. Desde tiempos ancestrales se han utilizado las plantas aromáticas y medicinales para múltiples propósitos y se continúa usándolas, tanto frescas como transformadas en aceites, sobre todo para fines farmacéuticos, culinarios y para industrias cosméticas y de producción de miel (Verlet, 1992; Lange, 1998). De hecho, el área dedicada al cultivo de plantas aromáticas y medicinales en España es aproximadamente de 7.000 ha, de las cuales 4.000 se dedican a la lavanda. El área en producción ecológica es actualmente de 2.300 ha, de las cuales 1.700 ha están en Andalucía. El mantenimiento del cultivo de este tipo de plantas puede constituir una actividad económica importante para los agricultores en las zonas productoras. (Blanco et al., 1996, 1998). En el capítulo II de la presente memoria, se estudia la respuesta de la erosión y escorrentía frente a la implantación de diferentes plantas aromáticas y de vegetación nativa y espontánea en los taludes de las terrazas de cultivo, paralelamente se evaluá la pérdida de nutrientes y carbono orgánico y el transporte de metales pesados por medio de parcelas cerradas de erosión (Foto 2).

La descomposición de la hojarasca de las plantas se define como el conjunto de procesos físicos y químicos que se producen para convertir esta materia en sus elementos químicos constituyentes. Como tal, es el proceso más importante del ciclo de los nutrientes de la mayor parte de los ecosistemas terrestres (Swift y Anderson 1989; Van Vuuren et al., 1993; Aerts y De Caluwe, 1997). Es un proceso que se ha estudiado con profundidad en diversos ecosistemas de climas tropicales y subtropicales, semiáridos, templados y mediterráneos. Sin embargo, la mayor parte de estos estudios se han llevado a cabo en ecosistemas forestales, existiendo muy pocos en sistemas de cultivo. Por ello, en el capítulo III se realiza un extenso estudio de descomposición de hojarasca mediante la técnica de las bolsas (litterbag technique) (Foto 3). El objetivo fundamental fue comparar las tasas de descomposición y el reciclado de nitrógeno de las especies predominantes de dos tipos de ecosistemas en pendientes: por una parte, el ecosistema de laderas alteradas (AES en el texto), que consiste en el cultivo de plantas subtropicales; en este tipo de escenario también se incluyeron plantas aromático-medicinales como medida para el control de la erosión de los suelos de los taludes; y por otra parte, el ecosistema de laderas no alteradas (UES en el texto), que consiste en una mezcla de plantas anuales junto con distintas plantas perennes de tipo matorral.

La contaminación difusa por productos procedentes de la agricultura tradicional (fertilizantes, herbicidas, fungicidas…etc) está degradando las aguas superficiales y subterráneas de gran parte de Europa, quedando muchos países muy lejos de cumplir los objetivos establecidos por la Directiva Marco de Aguas (WFD 2000/60 EC). En este contexto, en la zona de estudio, además de los problemas de erosión y escorrentía que se generan en estos terrenos aterrazados con frutales subtropicales, la sustitución de la vegetación espontánea por estos cultivos, provoca que los ciclos naturales se alteren y los nutrientes sean transportados por el suelo erosionado y el agua de escorrentía. Además, esta agricultura intensiva requiere aplicaciones importantes de fertilizantes para la producción de frutos. En este sentido, los fertilizantes nitrogenados (N) son la fuente principal del lixiviado de nitratos (Follet, 1989) y pueden disminuir la calidad del agua (Ren et al., 2003). Según Follet (1989), el lixiviado de nitratos depende fundamentalmente de diversos factores como la textura del suelo, la absorción por parte de las plantas, los fertilizantes aplicados y los procesos de transformación del nitrógeno. El fósforo (P), a pesar de ser esencial para el crecimiento de las plantas, se aplica con frecuencia por encima de las necesidades de las plantas. El P, junto con el N, es normalmente el nutriente limitante de la producción primaria el lagos y embalses. Por ello, un nivel alto de estos elementos aumenta la producción primaria y la demanda de oxígeno, provocando la eutrofización de aguas superficiales (Sharpley y Smith, 1990). Por otra parte, las altas concentraciones de potasio (K) en aguas de escorrentía y subsuperficiales parecen tener menos efectos críticos en las aguas subterráneas y en el medio ambiente en general. De hecho, en la mayoría de las regulaciones legales sobre aguas no se establecen concentraciones límite para este elemento. En este contexto, la Comunidad Europea fijó como límite máximo para agua de consumo humano 12 mg L^{-1} (EEC, 2000).

Muchos autores (Syvertsen y Sax, 1999; Kramer et al., 2006; Godlinski et al., 2008) afirman que uno de los mejores métodos directos para investigar la percolación de estos nutrientes (NPK) a las aguas subterráneas es el uso de los lisímetros, que consisten en una columna confinada de suelo, con un sistema de muestreo del agua que percola (Foto 4). Además, el cálculo de la evapotranspiración del cultivo (ET_C) es esencial para una gestión del riego eficiente. Las medidas de la evapotranspiración y de los coeficientes de cultivo (Kc) en plantaciones adultas de mango (*Mangifera indica* L.) y chirimoyo (*Anonna cherimola* Mill.) son desconocidas en este tipo de clima subtropical mediterráneo. Así pues, en el capítulo IV, se expone un estudio en el que se utilizan lisímetros de drenaje para determinar el impacto medioambiental de la agricultura tradicional e intensiva en cultivos de mango y chirimoyo en terrazas para (i) determinar la calidad y cantidad de las aguas lixiviadas a través del perfil del suelo, (ii) evaluar las cantidades de N, P y K para establecer un balance en el sistema suelo-agua-planta y (iii) determinar el uso del agua por medio de la estimación de los coeficientes de cultivo (Kc) para mango y chirimoyo.

Finalmente, el cultivo de especies subtropicales en este tipo de ambientes ha provocado diversos problemas en el uso y aprovechamiento del agua de riego. Es un hecho de sobra conocido que la disponibilidad de agua se está convirtiendo en un problema de dimensiones globales y se ve agravado en la cuenca mediterránea, por las propias características de este tipo de clima. En España, el uso del agua para agricultura supone un 80% del total del consumo (MMA, 2000). Por lo tanto, se hace cada vez más urgente la necesidad de establecer estrategias para el uso eficiente y sostenible del agua de riego. El capítulo V de la presente memoria estudia la respuesta de la producción de mango a diferentes regímenes de riego, asimismo, sobre el crecimiento del árbol, la dinámica del agua en el suelo y el estado nutricional del cultivo (Foto 5).

Hallar una armonía en el sector agrícola entre la necesidades de obtener un beneficio económico y la aplicación de medidas que eviten la degradación del medioambiente es uno de los grandes retos de futuro. Tampoco no es fácil, cómodo ni barato, solucionar los complicados problemas medioambientales planteados debidos a la agricultura, pero cada día tenemos más conocimientos y más medios para intentarlo, sin embargo, mal se puede conservar el medioambiente mientras el lucro y el provecho sigan siendo la primera aspiración de la sociedad.

Capítulo I

Land use changes in a small watershed in the Mediterranean landscape (Almuñécar, SE Spain): environmental implications of a shift towards subtropical crops

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(En revisión)

Land use changes in a small watershed in the Mediterranean landscape (Almuñécar, SE Spain): environmental implications of a shift towards subtropical crops

Rodríguez Pleguezuelo, C.R.[a*], Durán Zuazo, V.H.[a,b], Francia Martínez, J.R.[a], Martín Peinado, F.J.[c]

[a] IFAPA Centro Camino de Purchil. Aptdo. 2027; 18080 Granada, Spain.
Phone: (+34) 958 895 255; (+34) 647 199 854. Fax: (+34) 958 895 202;
*corresponding author E-mail: *crocio.rodriguez@juntadeandalucia.es*
[b] IFAPA Centro Las Torres-Tomejil. Crtra Sevilla-Cazalla, km 12.2; 41200 Alcalá del Rio (Sevilla) Spain.
[c] Departamento de Edafología y Química Agrícola, Universidad de Granada, C/Severo Ochoa s/n, 18071-Granada, Spain.

ABSTRACT

Resource use and watershed management has become an increasingly important issue in many countries, stressing the need to find appropriate management approaches for improving natural scenarios as well as agricultural landscapes of rural mountain areas. We analysed land use changes from 1978 to 2007 in a selected representative watershed of Almuñécar (SE Spain) using topographical maps, aerial photographs and interviews with farmers. In 1978 the watershed consisted of 64.2% almond orchards, 24.7% fallow land, 6.7% vineyard, 1.9% olive orchards and 2.5% other use. In 2007 much of the traditional orchards had disappeared, leaving only 17% almonds and 0.6% vineyards. Not less than 29.8% had become shrub land and another 24.6% abandoned crop land. However much land is now under subtropical crops: 19.2% avocado (*Persea americana* M.), 3.9% mango (*Mangifera indica* L.), 2.4% of loquat (*Eriobotrya japonica* L.) and 1.1% of cherimoya (*Anonna cherimolia* M.). This more intensive irrigated agriculture with subtropical trees on terraces could exacerbate impact on watershed degradation in these mountainous areas and could become a core problem with serious implications for sustainable resource use and environmental effects. In addition an expansion of the area under greenhouses and farmhouses was found within the watershed.

The type of housing has shifted from traditional farmhouses to residential, second, houses. The abandonment of traditional terraces with rainfed crops has led to the re-emergence of native spontaneous vegetation, promoting a denser plant cover and subsequent decrease of erosion. Therefore, highlighting the need for implementing sustainable conservation practices is crucial as part of future agricultural support.

Keywords: Land use type, subtropical crops, terraces, land use change, Mediterranean watershed

1. Introduction

Land use changes play an important role in the current global change phenomena. It is directly related to food security, human health, urbanisation, biodiversity, transboundary migration, environmental refugees, water and soil quality, runoff and sedimentation rates (Burel et al., 1993; Fu et al., 1994). Over the millennia, land use changes have transformed the ecosystems of the Mediterranean basin, being subject to the vagaries and complexities of social, political, economic, and even cultural and religious factors (Wainwright, 1994; Grove, 1996; Margaris et al., 1996). Moreover, industrialisation and pressure from tourism during the 20th century has led to a major socioeconomic change in rural areas, based on the abandonment of marginal terraced hillside land in favour of cash-crop cultivation of better soils in the plains, providing far higher net outputs (Puigdefábregas, 1998).

In this sense, traditional elements of the Mediterranean landscape provide habitats for organisms and thus maintain biodiversity. These elements include hedgerows, irrigation ditches, rough pastures, ponds and terraces. Terracing, an agricultural technique for collecting water and reducing soil erosion, has an ancient history of transforming landscapes into stepped agroecosystems in the Mediterranean basin, as well as in many mountainous regions of the world (Goudie, 1986; Denevan et al., 1987; Sandor et al., 1990; Hillel, 1991; Xing-guang and Lin, 1991; Treacy and Denevan, 1994; Zurayk, 1994; Beach and Dunning, 1995; Gardner and Gerrard, 2003). The main purpose of these structures in the past and also at present has been to increase the usefulness of steep slopes. In addition, they also may be used to boost the agricultural potential of slopes that could be cultivated without levelling. Throughout the Mediterranean region, and also in the traditional dry-land farming in south-eastern Andalusia (S Spain), soils on sloping land and cultivated for thousands of years have been gradually degraded by soil erosion. Currently, terracing continues, sometimes with heavy financial investment, resulting in pronounced alterations in the soil profile. According to Posthumus and de Graaff (2005), the benefits of terracing are: (1) improved water availability due to water conservation, (2) decreased nutrient losses due to the reduction of soil erosion, improving nutrient availability and boosting crop yields, (3) extended lifetime of land for cultivation, and (4) amelioration of otherwise limited cropping conditions on steep slopes.

Approximately since the 1950s and as a consequence of the rural exodus, many rural Spanish regions have undergone changes in their landscape structure due to the abandonment of agricultural activities and, in some cases to the proliferation of other economic activities, such as tourism. Particularly, on the coast of Granada (SE, Spain), as in other areas along the Mediterranean coast, human impact has been historically very strong (Fernández et al., 1992). The economy of the coast of Granada has been based on tourism, mainly since 1970s. Particularly, in Almuñécar, during 2001, according to the official population census (Instituto de Estadística de Andalucía, IEA, 2001), only 7.2% of the active population was employed in the agriculture and fisheries sectors, whereas 55.5% was involved in the tourism and services sectors. However, in the late 1980s, intensive irrigated agricultural systems were established with tropical and subtropical crops in the mountainous areas near the coast after the construction of machinery-made terraces. These structures are being used to cultivate avocado (*Persea americana* Mill.), mango (*Mangifera indica* L.), loquat (*Eriobotrya japonica* L.), cherimoya (*Annona cherimola* Mill.), litchi (*Litchi chinensis* Sonn.) and others (Durán et al., 2003; 2006a). The new terraces have profoundly transformed the traditional landscape of this area, since old terraces were cut by hand and built of stone. However, current terrace construction uses heavy machinery and high economic investment approximately amounting to 3,300 € ha^{-1}.

Here, we analyse land use types in the agricultural landscape from 1978 to 2007. Particularly focused on the influence of socio-economic changes promoted by land use changes in a pilot watershed located in Almuñécar (SE Spain), which is representative of adjacent watersheds in the study area, and furthermore highlights the need for adopting sustainable environmental policies in many areas of the Mediterranean basin.

2. Material and methods

2.1 The study area

The study area consists of a small agricultural watershed of 343 ha belonging to the Almuñécar and Itrabo municipalities (south-eastern Spain). It is located approximately 57 km south of the city of Granada and some 1.7 km north the city of Almuñécar (Fig. 1).

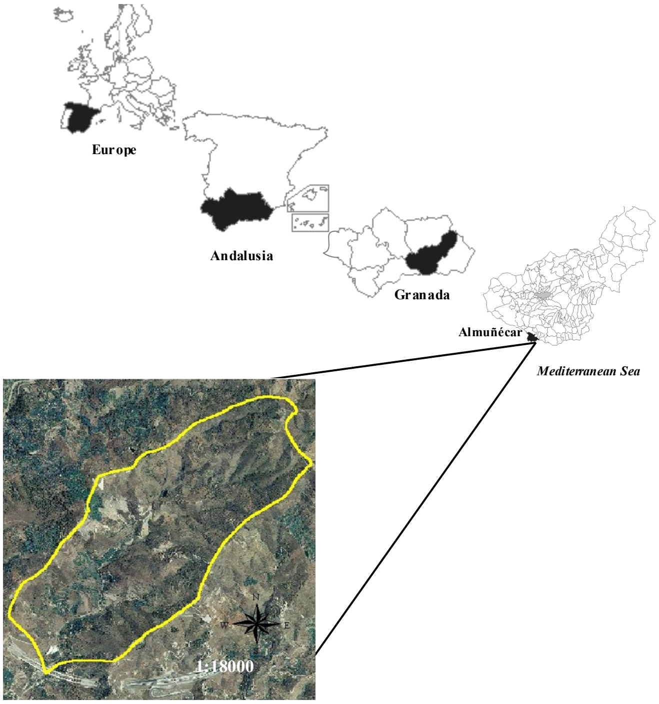

Figure 1. Location of the watershed in south-eastern Spain

During the summer the watershed had only base flow, peaking in December-January, the months of heaviest rainfall. Figure 2 shows the seasonal stream flow. Despite some light rains, it is lowest during July and August, because the watershed storage becomes exhausted and the rainfall has to fulfil the evaporation, transpiration and soil-storage demands before generating runoff.

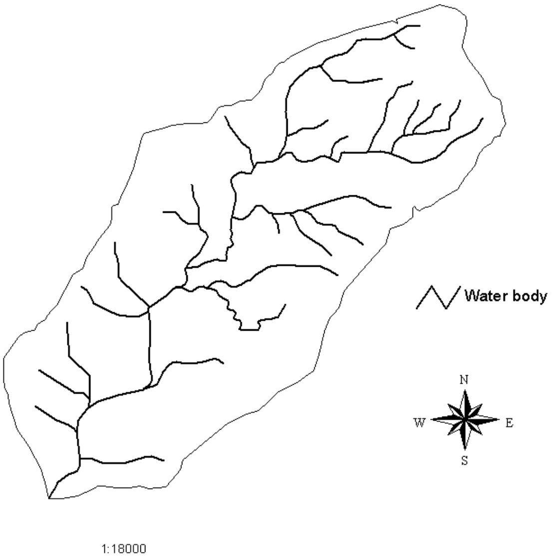

Figure 2. Water body system in the watershed.

The watershed ranges in altitude between 80 and 720 m, and the topography is mountainous with an average slope exceeding 50% and it shows features similar to those found in other Mediterranean mountain zones (Fig. 3). Local temperatures are subtropical to semi-hot within the Mediterranean subtropical climatic category (Elias and Ruiz, 1977). The average annual rainfall in the study zone is 449.0 mm. The proximity to the sea and to the Penibetic mountain system in the north reduces the influence of the northern winds, which result in a unique microclimate in Europe and suitable for subtropical farming and greenhouses (Frontana, 1984). The soils, formed from weathered slates, have a low degree of development. The main soil types are Eutric Regosols (FAO, 1998), Typic Xerorthent (Soil Survey Staff, 1999), occupying around 80% of the study area; the texture of these soils is dominated by sand (> 650 g kg^{-1}), with a low clay content (< 150 g kg^{-1}), gravels being frequent in depth; the pH is close to neutrality, the cation-exchange capacity low (frequently < 10 $cmol^{+}$ kg^{-1}); and the organic matter is generally below 15 g kg^{-1} (Aguilar et al., 1986). Other soil types are less abundant in the area, the Eutric Leptosols (FAO, 1998), Litic Xerorthent (Soil Survey Staff, 1999), occupy around 15% of the study area, and are directly related to the slopes steeper than 50%; the thickness is generally less than 10 cm, being related to the areas were the erosion process occur. Finally, in the Eutric Fluvisols (FAO, 1998), Typic Fluvaquent (Soil Survey Staff, 1999), appears in about 5% of the area, being restricted to the eventual watercourses.

The accumulation of material eroded from the slopes generates soils with depths greater than 60 cm but with a very high content in gravels and stones.

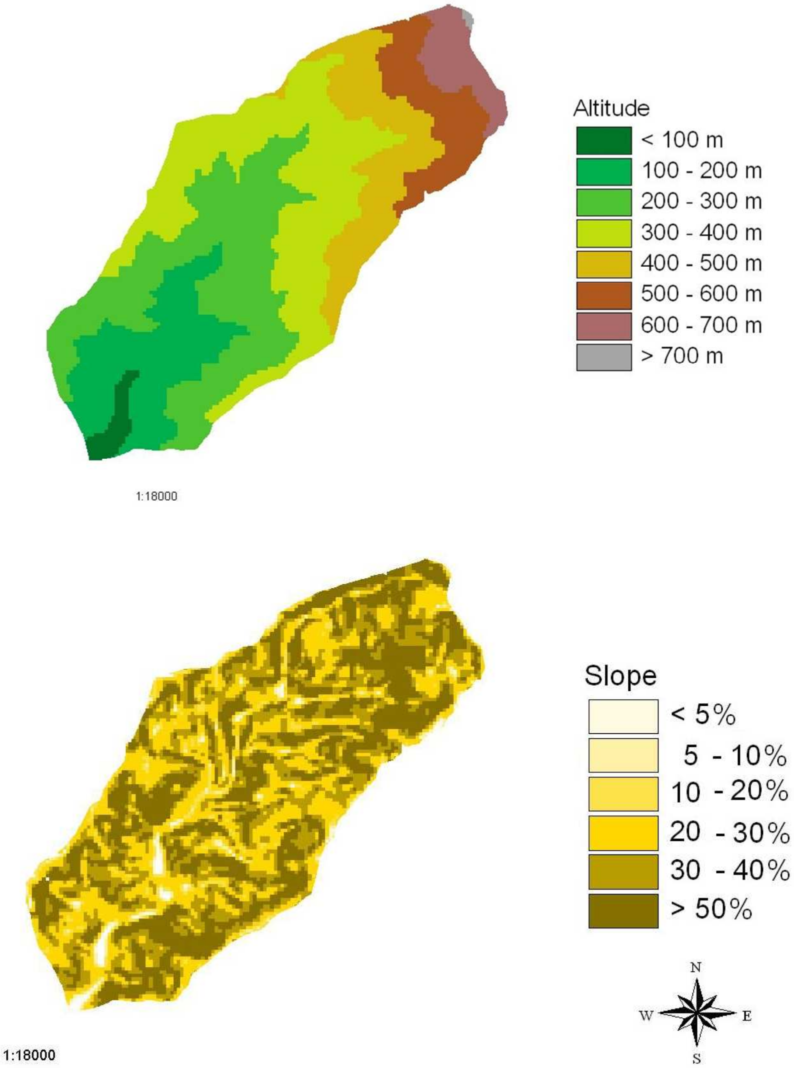

Figure 3. Altitude and slope maps of the watershed

2.2. Methods and execution

An integrated approach of digital image processing of satellite data combined with GIS was carried out for resource assessment (orthophoto scale 1:50,000, 2007; topographic maps of 1:50,000, 1978 and land-use maps of 1:50,000 for 1978, 1:10,000 for 2006 were used). In addition, a customized interview was conducted with farmers in the field.

This small watershed was chosen as an area with typical features and changes similar to the rest of the watersheds located in the area. A vector database was created by digitizing the 1978 and the 2007 topographical maps so that we could delineate the land-use types using the land boundaries.

Firstly, we created a layer for 2007, then we worked backwards to create a layer for 1978. The older map was used only to identify changes that have occurred. Possible distortions and projection errors in the older map were visually corrected so that it conformed to the newer map, which was more accurate. All land was classified into the following land use types (LUT's): olives, almonds, vineyards, fallow, abandoned cropland, shrub land, and subtropical crops (*e.g.,* mango, cherimoya, loquat, and avocado). Also, for this study we took into account the water bodies, farmhouses, and greenhouses. We evaluated the changes in LUT's from 1978 to 2007 to determine the extent of the landscape changes and we undertook field interviews and consulted local government to find out why these changes had occurred.

3. Results and discussion

3.1. Traditional Mediterranean LUT's

The LUT maps for 1978 and 2007 are shown in Figure 4. The major land use type was in 1978 almond orchards, with 64.2% of the watershed area, followed by fallowed grain land with 24.7% and vineyards with 6.7%. In 2007 the percentages for almonds and vineyards were reduced to only 17 and 0.6% respectively, whereas olive and fallowed grain land had disappeared altogether (Table 1). Rainfed crops such as olives, almonds and vineyards expanded rapidly during the 1970s on marginal land in many semi-arid environments, as pointed out by many other authors (Faulkner et al., 2003; Tubuleih et al., 2004; Ramos and Martínez-Casasnovas, 2007). Abandonment of olive cultivation in our study area was due to the more profitable new irrigated crops, and also due to several factors affecting olive cultivation in general, that is, the competition with other regions having a comparative advantage that influences their economic sustainability. Another important reason is the dependence on the governmental economic policy, concretely on production subsidies, as well as on other regional measures such as aid for less-favoured areas and agro-environmental subsidies (Duarte et al., 2008).

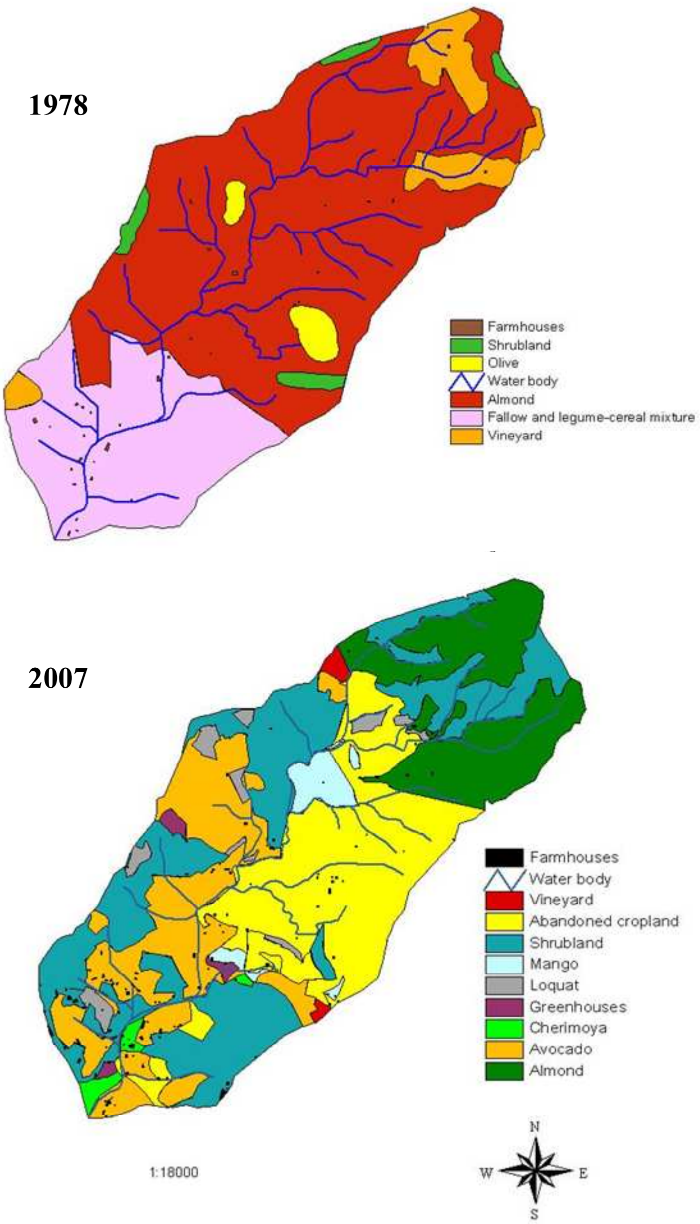

Figure 4. LUT dynamics for watershed from 1978 to 2007

Table 1. Land use types (LUT's) in the watershed from 1978 to 2007

LUT	1978		2007	
	(ha)	(%)	(ha)	(%)
Almond	220.6	64.2	58.3	17.0
Fallow with legume-cereal mixture	85.0	24.7	-	0.0
Vineyard	22.9	6.7	2.0	0.6
Olive	6.5	1.9	-	0.0
Avocado	-	-	66.1	19.2
Cherimoya	-	-	3.9	1.1
Loquat	-	-	8.2	2.4
Mango	-	-	13.5	3.9
Shrubland	6.7	1.9	102.5	29.8
Abandoned cropland	-	-	84.5	24.6
Greenhouse	-	-	2.4	0.7
Farmhouse	0.5	0.2	1.2	0.3
Water body	1.5	0.4	1.2	0.3
Total	343.7	100.0	343.7	100.0

On the other hand, in 1978, an important part of the studied area was dedicated to fallow land in rotation with a mixture of legume-cereal mixture (24.7% of the total area) (Table 1). This was part of the predominant agriculture, the use of synthetic inputs not being necessary to recover soil fertility, but leaving the land free from cultivation for some time. This agricultural system can also be considered as a traditional Spanish rural activity with food production for own use.

3.2. Shrub land

The shrub land area was increased from 6.7 ha in 1978 to 102.5 ha in 2007, which is due to abandonment of almond orchards within the watershed. This LUT consists of a scattered matorral of medium height with *Stipa tenacissima, Genista umbellata* subsp. *equisetiformis, Rosmarinus officinalis,* and *Anthyllis cytisoides* as dominant species from the *Asparago-Ramnetum oleoidis* association, which results from the degradation of a denser and taller forest of the association *Olea ceratonium* (Rivas and Rivas, 1971). Other species within the watershed include *Pinus halepensis*, *Juniperus phoenicea*, *Ononis tridentata*, *Thymus* *vulgaris*, *Papaver rhoeas*, *Convulvulus* sp., *Malva sylvestris*, *Reseda phyteuma*, *Anacyclus* sp., *Sinapis arvensis*, *Medicago* sp., *Chrozophora* sp., *Taraxacum officinale*, *Chenopodium* sp., *Poa annua*, *Bromus* sp., etc. Thus, the restoration of native vegetation took place in the watershed in those areas where farmers abandon cultivation basically due to the migration of young generations from rural areas to the main cities seeking economic opportunities.

3.3. Subtropical crops

According to the results of the present study, new tree crops established within the watershed cover 26.6% of the area. Part of the traditional rainfed cultivation of almonds and fallow areas was converted to irrigation and the entire olive area was turned into subtropical orchards (91.7 ha). Also, in recent years these new irrigated crops were established mainly on new orchard terraces. The most extended subtropical crop was avocado, grown on 66.1 ha, representing 19.2% of the area (Table 1). The cultivation of avocado on the coast of Granada was initiated at the beginning of the 1960s and it showed a strong expansion during 1980s. Currently, there are a total of more than 2,800 ha on the coast of Granada, with an annual expansion rate of 40 ha. About 60% of the avocado produced on the Granada coast is exported to the European market, since this fruit is much more appreciated than those coming from overseas, which are usually of lower quality due to the time of transport (Pedrosa, 2008). The most important cultivars in the studied watershed are “Hass” (with 75% of the total area) followed by “Fuerte”, “Bacon”, “Reed” and “Pinkerton”. The most important problems of avocado cultivation on terraces, as for the rest of crops in the area, is the excessive cost of energy required for pumping up irrigation water to high levels. Other problems of avocado cultivation in the study area include the spider mite (*Oligonychus perseae*) and iron chlorosis that negatively affects its production. This spider can not be treated chemically, although on the coast of Granada and Malaga some 3,500 ha are already affected by this mite. Finally, another problem is the large size of the trees due to the high application rates of N-fertilizers on terraces, which reduces the number of fruits in relation to canopy, slows down the manual harvest of the crop, and leads to a high risk of nitrogen pollution of water bodies (Rodríguez et al., 2009a).

A new subtropical crop, cherimoya, not yet found in the watershed in 1978, covered in 2007 an area of 3.9 ha (Table 1) in 2007. This exotic fruit has a strongly expanding European market (Lüdders, 2002). Globally, Spain is the first cherimoya producer in the world with about 3,600 ha, (and total production of 35,000 t), followed by Perú (1,800 ha) and Chile (1,200 ha) (Van Damme and Scheldeman, 1999). In the study watershed, as in the rest of the coast of Granada, the most important cultivars are “Fino de Jete” and “Campas”. These crops were brought by Andalusian emigrants, when they returned back from America during the 16th to the 18th centuries. However, the crop began to be cultivated at the beginning of 19th century, most specimens being a crossing between the varieties brought from America and those grown in Río Verde valley (Almuñécar). The expansion of this crop took place after the Spanish Civil War (1936-1939). In 1941 there were 55 ha of cherimoya on the coast of Granada. Today, most cherimoya orchards on the Granada coast are located in flat areas, and 90% of this fruit is consumed in Spain and the remaining 10% is exported to EU countries.

Loquat is another important crop on the coast of Granada. According to the results of this study there are 8.2 ha in the studied watershed in 2007 (Table 1). Unknown in the Western world until the 18th century, the easy adaptation of loquat to the Mediterranean climate has permitted its rapid expansion throughout the Mediterranean basin. China is the world’s largest producer of loquat with more than 314,000 t, and Spain is the second world producer of this fruit, accounting for 84% of exports worldwide (Caballero and Fernández, 2004). In the studied watershed the most common cultivars are “Golden Nugget”, “Algerie” and “Tanaka”, which are considered the most marketable cultivars (Martínez et al., 2000). This crop needs intensive field labour because of the pruning, and inflorescence and fruit thinning are made by hand. The trees are usually planted in a single row on terraces with platforms of 3-4 m wide that hinder the mechanization of loquat plantations as it does for other subtropical species within the watershed.

Mango is also an emerging crop in the study watershed, not existing in 1978. Table 1 shows the area dedicated to this crop in the watershed of 13.5 ha in 2007, with a high increasing trend of mango cultivation in this marginal area (Durán et al., 2006b). In this context, the world production of mangoes is estimated to be over 28.5 million tonnes per year and it is grown commercially in more than 90 countries. Asia produces 77% of the world production, America 13% and Africa 9%. In 2005, global exports reached 912,853 t, for a total of 543.10 million USD (FAOSTAT, 2007). As Spain is the main EU producer of tropical and subtropical fruit, in 2000, the EU imported a total of 6,647 t of mangos from Spain (from a total of 117,102 t imported globally) (Cohen et al., 2001). In Spain, cultivation is feasible primarily in the provinces of Granada and Málaga, with some 900 ha of mango orchards soon to exceed a production of 6,000 t yr^{-1}, which most of them are Florida cultivars (Campbell and Campbell, 1993). Within the watershed, as in the adjacent watersheds, the most extensively produced and commercial cultivar is cv. Osteen, having an average weight of 527.1 g, length of 127.1 mm, width of 90.7 mm and pulp-seed ratio of 88.2% (Calatrava et al., 1992; Rodríguez et al., 2009b).

3.3.1. Implications for the environment

The intensification of irrigated agriculture in the watershed has led to the use of chemical products in order to maximize production. Particularly this type of agriculture, based mainly on subtropical crops, relies on the use of chemical fertilizers, herbicides, fungicides, insecticides, plant growth regulators, etc. Table 2 shows a summary of water and fertilizer inputs for subtropical crops existing in the watershed. On average, avocado is the crop with highest fertilizer requirements. However, loquat and mango require more water due to the higher number of trees per hectare (400-600 trees). The cultivation of subtropical crops in the watershed has increased water consumption, usually coinciding with the dry season and with the highest water demand for tourism. Meanwhile, farmers often apply higher nutrient rates (NPK) than required by the crops, and such excesses represent potential environmental pollution, requiring a detailed assessment of nutrient balances (Rodríguez et al., 2009a). Consequently, high fertilizer application in subtropical intensive agriculture is often one of the main sources of nutrient leaching to the environment, associated with a reduced quality of groundwater and surface waters (Wolf et al., 2005, Rodríguez et al., 2009a, 2009c). Thus, there is an urgent need for improving the water-use efficiency, and consequently, the rational use of natural resources (Carta Europea de Ordenación del Territorio, 1983; Instituto de Recursos Naturales, 2002, Rodríguez et al, 2009b).

Table 2. Average water consumption and use of nutrients for irrigated subtropical crop within the watershed

Crop	Water consumption 0-5 years trees	 5-10 years trees	 Mature trees	Nutrient use Nitrogen	 Phosphorus	 Potassium
		(m^3 ha^{-1} yr^{-1})			(kg ha^{-1})	
Mango	482	2,892	2,903	165	49	140
Cherimoya	268	1,608	2,150	145	24	103
Avocado	240	1,440	2,400	287	150	275
Loquat	446	2,223	2,969	200	120	160

Conversion of sloping land into terraced land for cultivating subtropical crops could deteriorate soil properties, especially reducing soil organic matter and changing the distribution and stability of soil aggregates, above all in bare-soil areas (taluses) (Durán et al., 2005). According to Rodríguez et al. (2009c), the taluses of new orchard terraces with subtropical crops that are totally unprotected from vegetation, urgently need the implementation of plant cover in order to control erosion and nutrient transport, and to protect the terrace structure. In addition, plant cover in this type of environment promotes the atmospheric carbon sequestration and recycles the nutrients (Rodríguez et al., 2009d). Thus, the increased agricultural activity has intensified pressure on this fragile high-altitude ecosystem, and it will be urgent to implement agro-environmental strategies in order to mitigate this impact.

Another important consequence of the intensification of agriculture in the area is the overexploitation of the Río Verde aquifer existing in the watershed. Due to the scarcity of fresh surface water resources during drought years the water supply is usually covered by the exploitation of aquifers, leading sometimes to marine-intrusion processes which increase groundwater salinity (Calvache and Pulido, 1996), and therefore, affecting the irrigation wells and plantations that use this water for irrigation (Durán et al., 2004). In this connection, there are 510,000 illegal wells in Spain. This means that at least 45% of all water pumped from aquifers each year is extracted without regard to legal constraints (WWF, 2006), and the same situation is reflected in our study watershed, where there are no official numbers of these illegal structures.

3.4. Abandoned cropland

Another important LUT in our studied watershed is the increase of abandoned cropland, which represents some 25% of the current scenario (Table 1). In recent past, the entire land was cultivated mainly with the purpose of self-sufficient agriculture and also for obtaining wood as an energy source. However, the abandonment of marginal agricultural landscapes has been a widespread phenomenon in European Mediterranean areas since the second half of the past century (Margaris et al., 1996; Puigdefábregas and Mendizábal, 1998). Likewise, agricultural land abandonment promotes widespread changes in the composition and spatial arrangement of the plant communities (Barbero et al., 1990), increasing the risk of severe wildfires (Vallejo et al., 2005). The ancient terraces (bench type with hand-made stone walls), most occupied by almond orchards, have been progressively abandoned. These structures protected the soil and preserved the natural vegetation. Nowadays, the taluses of new orchard terraces occupied by subtropical crops are totally unprotected from vegetation because local farmers usually leave bare soil, promoting a progressive collapse mainly due to soil erosion (Durán et al., 2005). According to Rodríguez et al. (2009c), for protecting the structures of terraces and soil conservation, it is crucial to promote the use of plant cover. In this context, it has been demonstrated that abandonment of traditional extensive cultivation in the Mediterranean basin has different impacts on soil-sediment losses according to the slope gradient, as pointed out by Koulouri and Giourga (2007). In the watershed abandoned old terraces are gradually restored by native spontaneous vegetation, protecting soil from erosion.

3.5. Greenhouses and farmhouses

Currently, there are 2.4 ha of greenhouses within the watershed that were not yet existing in 1978 (Fig. 4). These structures are basically low-cost, unheated plastic-covered frames and with soil-grown crops. This expansion of greenhouses is the result of the successful initiatives carried out by the local farmers. Moreover, the greenhouses are very profitable due to high European prices for horticultural crops (Castilla, 2004). However, this activity involves a high consumption of energy and agricultural materials (*e.g.*, fertilizers, pesticides, herbicides, etc.) that can eventually pollute both surface and groundwater systems. In this context, the study area has been classified as “vulnerable” according to the “Diputación de Granada” (2002) due to the diffuse pollution caused by fertilizers. Nevertheless, after the 1990s, this growth slowed down due to the stabilization of market prices and the emergence of pests that affected production (Matarán, 2005). Currently, on the coast of Granada, several research projects are seeking to recover abandoned greenhouses and transform them into mango and cherimoya plantations in the study area (Anguita, 2008).

Land use changes are caused by a number of natural and human driving forces (Meyer and Turner, 1994). Whereas natural effects such as climate change are felt only over a long period of time, the effects of human activities are immediate and often radical and detrimental. In this context, the status of land cover and its dynamics have both local and regional environmental implications, because the consequences of degradation do not have clear boundaries. Particularly in our study area, the main driving forces which significantly affect land use are the highly profitable agriculture and tourism, which have interacted with factors and impacts on the landscape (Fig. 5).

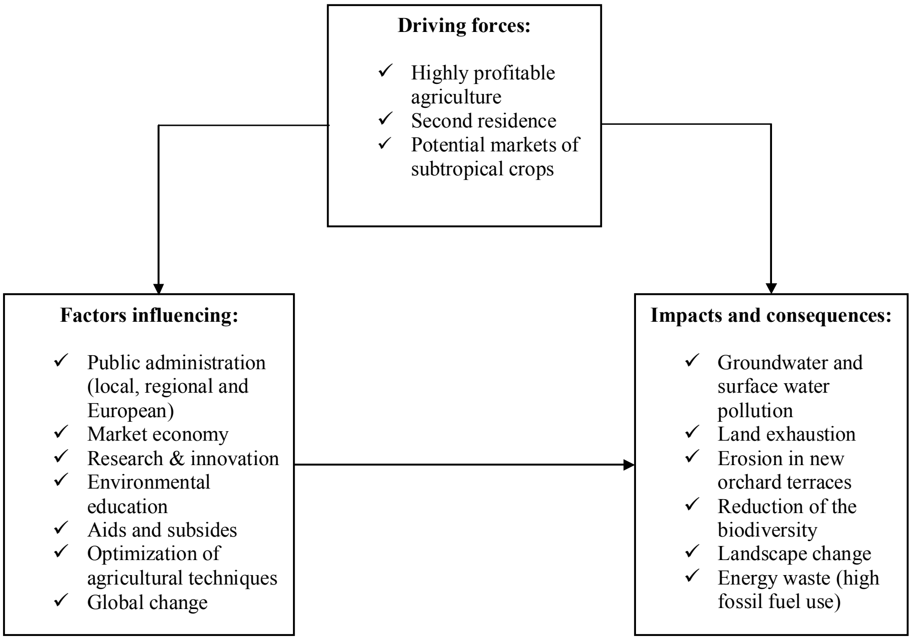

Figure 5. Factors, driving forces, and impacts in the study area

These two activities compete for basic resources such as water and available land (Costejá et al., 2002; Bröcker et al., 2004). The increase of tourism in our study area has been reflected by the building of holiday houses (second dwellings). In 1978 the area covered by farmhouses, occupied by Spanish farmers, was 0.5 ha while in 2007 the figure increased to 1.2 ha (Table 1). Our field research shows that these farmhouses are currently mostly small residences usually occupied by retired people from Belgium and France as a second residence. Some of the existing residences were agricultural farmhouses in the past, which were transformed in residences. According to the Official Census of 2003 (IEA, 2003) 70.4% of the foreign population residing in Almuñécar comes from the European Union (56.8% from 16 to 64 years old and 35.6% older than 65 years old). In this sense, local, regional and state governments are not efficiently implementing responses such as prosecution of illegal occupation for a sustainable spatial planning (Valenzuela and Matarán, 2008). Therefore, controlling the expansion of buildings and applying sustainable land use planning could constitute an adequate answer to diminish spatial conflicts and to preserve traditional landscapes (Atance et al., 2001; Abler, 2004). With respect to the accessibility of the area, a main road just at 2.7 km from our study area is currently being constructed (Main Road A-7, Autovía de Sierra Nevada, from north to south). While this type of infrastructure will give an important economic impulse to the area, it will at the same time have environmental costs and bring about a modification of the ecosystem and drastic land use changes (Serrano and Rosúa, 2008).

4. Conclusions

The present study highlights the importance of the impact of human interventions regarding land use and the urgent need to apply of conservation practices in an agricultural mountainous watershed in the Mediterranean region. Therefore, on the basis of the results of the present study and based to the current scenario LUT's we conclude the following:

- In the studied watershed, as well as in adjacent watersheds in the coastal area of Granada, the main driving forces affecting the land use types are agriculture, mainly based on subtropical crops, and tourism.
- These driving forces exert important pressures on the environment because of the intense use of natural resources (soil and water).
- It is necessary to promote and improve the equilibrium between water demand and water availability by a better land use planning, and by research on water requirements of the different existing subtropical crops in the area.
- After the abandonment of traditional (stone made) terraces in 1978 occupied by almonds and olives, new orchard terraces were built for subtropical crops, enhancing soil degradation problems (water erosion, soil nutrient losses, carbon losses, etc.).
- The establishment of subtropical crops on terraced hillsides required planned sustainable agricultural measures based on the analysis of water and nutrient balances in order to avoid water waste and to preserve groundwater from pollution by fertilizers.
- In this watershed, as in many others agricultural scenarios in the Mediterranean basin, land use changes are correlated with socioeconomic forces. Given the increasing trend in the cultivation of subtropical crops on terraces in the coming years along the coast of Granada, in future research priority should be given to the adoption and implementation and of sustainable environmental strategies for sustainable land use planning.

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Capítulo II

Environmental impact of introducing various types of plant covers in the taluses of orchard terraces: implications for erosion and agricultural runoff control

Enviado a *Pedosphere*

(En revisión)

Environmental impact of introducing various types of plant covers in the taluses of orchard terraces: implications for erosion and agricultural runoff control

Rodríguez Pleguezuelo, C. R.*[1], Durán Zuazo V.H.[1,2], Martín Peinado, F.J.[3], Francia Martínez, J.R.[1], Flanagan, D.[4]

[1] IFAPA Centro Camino de Purchil. Aptdo. 2027; 18080 Granada, Spain. Phone: (+34) 958 895 255; (+34) 647 199 854. Fax: (+34) 958 895 202
Email: *crocio.rodriguez@juntadeandalucia.es*
[2] IFAPA Centro Las Torres-Tomejil. Crtra Sevilla-Cazalla, km 12.2; 41200 Alcalá del Rio (Sevilla) Spain.
[3] Departamento de Edafología y Química Agrícola, Universidad de Granada, C/Severo Ochoa s/n, 18071-Granada, Spain
[4] NSERL, National Soil Research Laboratory 275 S. Russell Street, West Lafayette, IN 47907-2077, USA

ABSTRACT

South-eastern Spain, and in particular the coastal areas of Granada and Málaga, feature a large area under subtropical crops, with orchards established on terraces built along the slopes of the mountainous areas. The climate, characterized by periodically heavy rainfall, variable in space and time, and with the common agricultural practice of leaving the taluses with bare soil, are the main factors encouraging soil erosion, runoff, and subsequent transport of pollutants. Over a two-year period, six plant covers were applied [(*Thymus mastichina* (Th), *Lavandula dentata* (La), native spontaneous vegetation (Sv), *Anthyllis cytisoides* (An), *Satureja obovata* (Sa), *Rosmarinus officinalis* (Ro)] in comparison to a control of bare soil (Bs) to determine the effectiveness of the covers in reducing soil erosion, runoff, and potential pollution risk by agricultural nutrients and heavy metals. Also, carbon losses were monitored in the sediments of transported and eroded soil. For this purpose, 16 m^2 erosion plots (4 m x 4 m) were laid out in the taluses of the terraces. When the yearly data were compared, the control plot (Bs) shows significantly higher soil loss and runoff rates (26.4 t ha^{-1} yr^{-1} and 55.7 mm yr^{-1}, respectively) than the treatments with plant covers. The plant covers studied registered the following results in runoff: Ro > Sa > An > Th ≈ La > Sv (41.7, 38.2, 35.5, 16.9, 16.1, and 12.4 mm yr^{-1}, respectively) while annual soil erosion gave the following results: Sa > An > Ro > Th > Sv > La (18.0, 13.5, 13.4, 5.5, 4.4, and 3.2 Mg ha^{-1} yr^{-1}, respectively). This means that Sv reduced runoff and soil losses compared to Bs by not less than 78 and 83%, respectively. Nevertheless, La and Th plots were also very effective plant covers in reducing runoff and soil erosion (71.2 and 87.8; 69.5 and 79.2%, respectively) in comparison with the Bs plot. The heaviest nutrient losses in runoff and sediments were found in Bs and the lowest in the La, Th, and Sv plots. For the first study year, the total carbon losses followed the pattern: Bs > Sa > Th > Sv > Ro > La > An, while during the second year this trend changed, since carbon losses followed the pattern: Bs > Ro > Sa > An > La > Sv > Th. Bs and Ro plots registered the highest carbon losses (829.9 and 652.1 kg ha^{-1}, respectively), the lowest carbon-loss rates being measured in La, Sv and Th plots (145.2, 140.3 and 109.3 kg ha^{-1}, respectively). The results indicate that heavy metals (Mn, Cr, Co, Ni, Cu, Zn, Mo, Cd, and Pb) in these types of agroecosystems may also be a potential pollutant due to transport by agricultural runoff. There was a major reduction of heavy-metal transport by plant covers in relation to the control of bare soil. The results of this research support the recommendation of implementating plant covers with multiple purposes (aromatic-medicinal-culinary) on the taluses of subtropical crops terraces in order to reduce erosion and pollution risk.

Keywords: terraces, erosion, agricultural runoff, heavy metals.

1. Introduction

Soil has been termed by the International Soil Science Society as a “limited and irreplaceable resource”. Without this resource, the biosphere would collapse, with devastating effects on humanity. In this sense, soil erosion by water is the detachment of soil particles by the direct action of raindrops and runoff water, and the transport of these particles by splash and very shallow flowing water to small channels or rills. This environmental problem ranks as one of the most serious problems in the world and its effects are long lasting (Pimentel et al*.*, 1995), exerting both physical and chemical effects. Physical effects involve soil loss from agricultural fields and deposition in streams and water bodies, while chemical effects involve the loss of plant nutrients and other agricultural chemicals (Stroosnijder, 1995). The removal of these nutrients by erosion leads to negative nutrient balances and reduces land productivity

(Van den Bosch et al., 1998). In addition, most of the organic matter is close to the soil surface in the form of decaying leaves and stems, and therefore topsoil erosion also depletes soil organic matter. To date, all carbon-budget calculations have relied on the assumption that there are additions to the soil carbon pool in solid forms, the only losses are gaseous. Recently, this has been recognized as erroneous, since soils and landscapes are dynamic (Lobb et al., 2002). Transported soil material by erosion contains carbon and therefore influences the cycling of this element in soils (Lobb *et al.*, 2002).

The Mediterranean climate is characterized by unpredictable rainfall fluctuations from year to year with high-intensity rainfall events, increasing the vulnerability to erosion. Soil erosion is one of the major environmental problems in several areas of Spain, which have been described as the most threatened in Europe (Vallejo et al., 2005). This fact can be considered as the result of various factors: fragile natural ecosystems (irregular terrain with steep slopes), long-period of human exploitation, land misuse, and land abandonment (Kosmas and Danalatos, 2003; Thornes, 1996; Kosmas et al, 2000). These processes have been varying in space and time at least for the last 4000 years within the Mediterranean basin (Brandt and Thornes, 1996). Concretely in Spain, more than 22 million ha (43.8% of the land) are affected by erosion rates higher than 12 Mg ha^{-1} yr^{-1}, exceeding the tolerable limit of soil formation (Rojo, 1990). In 2006, 12.6% of the land was affected by erosion rates higher than 50 Mg ha^{-1} yr^{-1}, and 34.1% of the land had erosion rates from 10 to 50 Mg ha^{-1} yr^{-1} (DGB MMA, 2008).

Many mountainous areas in Spain have been terraced during the last few decades, and especially since the admission to the European Union in 1986, which has been one of the main driving forces for agriculture development. The main objective of these structures is to make use of steep terrains. Another subsequent function is soil conservation, accomplished by reducing the slope and allowing runoff from the talus of the terrace to infiltrate to the bench portion. According to Durán et al. (2003, 2006), along the coast of Granada (SE Spain), intensive irrigated agriculture has been established on these terraces on steep slopes with subtropical crops [avocado (*Persea americana* Mill.), mango (*Mangifera indica* L.), cherimoya (*Annona cherimola* Mill.), litchi (*Litchi chinensis* Sonn.), and others]. The detached soil from the taluses of orchard terraces accumulates on the platform of the terrace below, hindering manual fruit harvesting and orchard maintenance. In this sense, talus erosion, making terrace reconstruction necessary, poses a serious economic challenge for farmers. Local farmers usually eliminate vegetation from the taluses of the terraces because most of them are weeds. In addition, the importance of vegetation in controlling erosion and runoff is widely accepted. The relation between erosion and vegetation is the result of various complex processes that act at different time scales (Coppin and Richards, 1990; Morgan, 1986). In the short term, vegetation influences erosion mainly by intercepting rainfall and protecting the soil surface against the impact of rainfall drops, and by intercepting runoff. In the long term, vegetation influences the fluxes of water and sediments by increasing the soil-aggregate stability and cohesion and by improving water infiltration (Bochet et al., 2006; Durán and Rodríguez, 2008). Damage to soil-surface vegetation in arid and semiarid areas in not easily repaired and can lead to permanent degradation of the productive potential.

In the semi-arid Mediterranean region, most experimental studies on the influence of the natural vegetation on erosion have quantified soil loss and runoff under woodlands or shrublands comprising a mixture of plant species (e.g. Francis and Thornes, 1990; Romero Diaz et al., 1999; Dunjó et al., 2004). All of these studies concluded that typical Mediterranean shrubland vegetation is highly efficient in reducing water erosion.

When soil is eroded, plant nutrients such as nitrogen (N), phosphorus (P), and potassium (K) are lost.

Since topsoil is usually relative rich in nutrients, eroded soil typically contains about three times more nutrients than the soil left on the eroded land. Therefore, to offset the damages that erosion inflicts on crops, large quantities of fertilizers are intensively used. These extra inputs can harm human health and pollute the environment (Pimentel et al., 1995)

High P concentrations in surface waters are a major cause of eutrophication, with detrimental impacts on water quality, since P is usually the nutrient that limits algae growth in freshwater bodies. From an agronomic viewpoint, P losses represent a decline in nutrients for the system, to which the farmers usually attaches little importance due to the low prizes of fertilizers. However, from an environmental perspective, these losses can mean a serious deterioration in water quality. Although P tends to be adsorbed in the top 15 to 30 cm of soil, it can also move thorough soil and can be found in runoff water. In this context, in Europe, there has been a large-scale trend of increasing P concentrations in freshwater during the last few decades (European Environment Agency, 2003), and, concretely in the Guadalquivir river basin (the main watershed of Andalusia, SE Spain), 13% of reservoir is eutrophic (Ministerio de Medio Ambiente, 2005). On the other hand, nitrate (NO_3) is a common chemical pollutant in agricultural areas. In Europe, NO_3 concentration exceeding the international (WHO, 1993) recommendations for drinking water (50 mg L^{-1}) have been found in groundwater under 22% of cultivated land (Laegreid et al., 1999). In contrast to P, the NO_3 is highly soluble and generally does not adsorb to soils. Rather, NO_3 tends to move with water into the soil profile.

In general, nutrient losses are expected to be reduced in soil-management systems that preserve plant residues. However, under such conditions these residues can be washed off (Burwell et al., 1985), becoming sources of soluble nutrients, which can be lost by water erosion. The third major nutrient, kalium (K) is an important nutrient in fruit production, and therefore local farmers tend to apply heavy amounts of this element to encourage good-quality fruit.

Apart from theses three major nutrients, the increased inputs of heavy metals in soil have also received attention, since transport of these elements may result in increased contents of heavy metals in groundwater or surface water (Alloway, 1995; Moore et al., 1998). Heavy metals can be included in commercial fertilizers and other agrochemicals. Soils receiving repeated applications of these products could show increases in heavy metal concentration in runoff (Moore et al., 1998).

In our study area, since ancient times, aromatic and medicinal plants have had wide applications, and continue to be used fresh, frozen or dry, and also after processings into oils, extracts, and essences, primarily for the food, pharmaceutical, and cosmetic industries (Wijesekera, 1991; Verlet, 1992; Lange, 1998). Also, beekeepers use these plants during spring for honey (with different aromas and tastes), pollen, and bee-glue. A great amount of aromatic and medicinal products comes from wild plants, while more marketable species (mint, lemon balm, lavender, chamomile, etc.) are cultivated with conventional or ecological production systems. The cultivated area of aromatic and medicinal plants in Spain is roughly 7,000 ha, of which some of 4,000 ha are devoted to lavender production. The ecological production area is on the increase and, is currently about 2,300 ha, of which 1,700 ha is located in Andalusia. Therefore, the maintenance and cultivation of these types of plants constitute major economic activities for local farmers (Blanco et al., 1996, 1998).

An understanding of how vegetation disturbance and the construction of terraces for subtropical crop cultivation on the coast of Granada affects runoff and soil loss is urgently required in order to adapt soil management, to mitigate soil erosion effects and thereby move towards sustainable agriculture. The aim of this study was to test, under field conditions, the response of runoff, soil erosion, nutrient, carbon losses, and heavy-metal transport to different plant covers, including aromatic and medicinal plants and native vegetation during two hydrological years.

2. Materials and methods

2.1 Description of the study area

The study area is located in the south-eastern part of the Iberian Peninsula (Lat 36º48´00´´N, Long 3º38´0´W) (Fig. 1), some 7 km north of the Mediterranean coast at Almuñécar (Granada, SE Spain) at 183 m a.s.l.

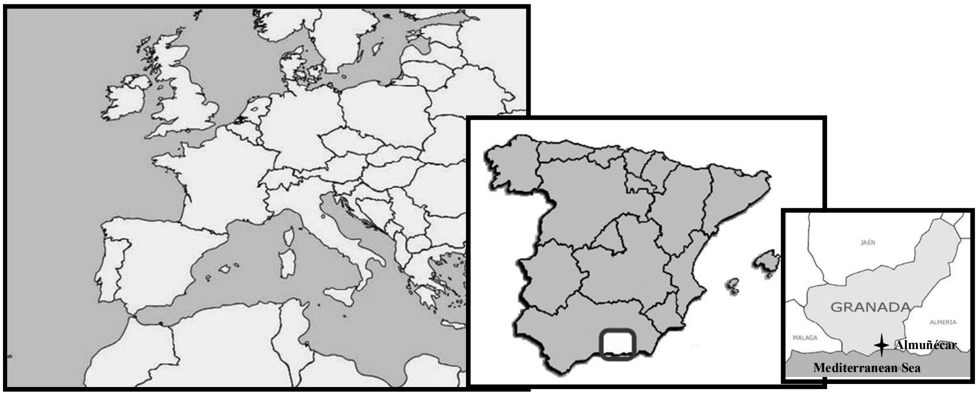

Figure 1. Location of the study area in south-eastern Spain (Almuñécar, Granada)

The relief is rough and steep, and most of the area presents slopes steeper than 30% , as reported at the plot and watershed scale by Rodriguez et al. (2009a) and Rodríguez et al. (2009b). The study terrace, representative of those commonly found in the study area, is a reverse-sloped bench-terrace type with a toe drain measuring 160–170 m long. The platform was 2–3 m wide and the talus 3–5 m high. The platform had a single row of bearing mango trees (*Mangifera indica* L. cv. Keitt) spaced 3 m apart. Local temperatures are subtropical to semi-hot within the Mediterranean subtropical climatic category (Elias and Ruiz, 1977). The average annual rainfall in the study zone is 449.0 mm. The soils, formed from weathered slates, vary in depth, and some are rocky, providing generally very good drainage, especially in the fill used to construct the platforms. The soils of the zone are Typical Xerorthent (Soil Survey Staff, 1999). The main characteristics of these soils are presented in Table 1.

2.2 Experimental field design

Fourteen closed plots of 4 m x 4 m (16 m^2) each were established on the taluses of the terraces. They were sufficiently wide to minimize edge or border effects. Each one consisted of a galvanized enclosure, drawer collector, sediment and runoff collector, and tanks for storing runoff. The boundaries of each plot were defined by 50 cm galvanized steel sheets and inserted up to 20 cm below the soil surface to prevent soil from leaving or entering the plot.

Table 1. Physico-chemical analyses from soil samples of 3-15 cm depth

Soil characteristics	
Slope (%)	214
Boulders	Slight
Textural class	Loamy sand
Sand (g kg^{-1})	684 ± 79
Silt (g kg^{-1})	228 ± 39
Clay (g kg^{-1})	88 ± 19
pH (H_2O)	7.7 ± 0.4
Organic matter (%)	0.79 ± 0.21
Available P (ppm)	9.0 ± 2.1
Assimilable K (mg kg^{-1})	175 ± 21
Nitrogen (%)	0.04 ± 0.02

n =28

To avoid the effects of position, all fourteen plots were established in one line, and they were oriented parallel to the slope and adjacent to each other (Fig. 2).

Five types of aromatic-medicinal-mellipherous plants were used as covers: *Thymus mastichina* L. (Th) *Lavandula dentata* L. (La), *Satureja obovata* Lag. (Sa), *Anthyllis cytisoides* L. (An) and *Rosmarinus officinalis* L. (Ro) each replicated twice. The planting grid was 40 x 40 cm, with approximately 81 introduced plants per plot. Also, two of the erosion plots were left with native spontaneous vegetation growing in the study area. (a spontaneous mixture of annual herbaceous weeds: *Papaver rhoeas*, *Convolvulus* sp., *Malva sylvestris*, *Reseda phyteuma*, *Anacyclus* sp., *Sinapis arvensis*, *Medicago* sp., *Chrozophora* sp., *Taraxacum officinale*, *Chenopodium* sp., *Poa annua*, *Bromus* sp., etc.). Finally, two erosion plots were left with bare soil as a control.

The climatic data were taken from a local weather station (<20 m from the plots). For each of the events, maximum intensity at 30 minutes (I_{30}), and kinetic energy were calculated ($KE = 210 + 89 \log_{10} I$) (Wischmeier and Smith, 1978; Brandt, 1990). The erosion index of a particular event was calculated by multiplying the kinetic energy of the rain by its maximum intensity (Wischmeier, 1976).

Figure 2. Closed erosion plot with the different studied treatments

2.3 Field work and laboratory analysis

Runoff and sediments were collected at the base of each plot. The runoff in each tank was measured and sampled after each rainfall event. Sediment concentration in runoff was determined in aliquots, which were decanted and dried at 105ºC. Sediment yield was calculated by multiplying the runoff volume (total water in the tanks) by the average sediment concentration.

Nutrient loss in runoff was expressed by the following equation:

$$\text{Total load} = \sum \text{nutrient conc. (mg L}^{-1}) \times \text{Total runoff depth (mm)} \qquad \text{(Eq. 1)}$$

Nutrient loss in sediment was expressed by the following equation:

$$\text{Total load} = \sum \text{nutrient conc. (mg kg}^{-1}) \times \text{Weight of sediments (kg m}^{-2}) \qquad \text{(Eq. 2)}$$

Each runoff sample was analysed for NO_3^-, NH_4^+, PO_4^{3-}, and K in accordance with standard methods for the examination of waters (APHA, AWWA, WPCF, 1995) and each sediment sample was analysed for N, P, and K content following standard methods for soil analysis (MAPA, 1994).

In addition, the heavy-metal concentration was also determined in each runoff sample by inductively coupled plasma mass spectrometry (ICP-MS) with a PerkinElmer SCIEX ELAN-5000A spectrometer

A representative sub-sample of the sediment was air-dried and analysed for organic carbon by weight differences after combustion at 550ºC for 2.5 h (Head, 1984).

In each field plot, soil-surface samples (0-25 cm) were taken at the beginning of the study, and after 12 and 24 months in all the plant covers in order to study the evolution of soil organic matter, using standard soil-examination methods (MAPA, 1994). All soil samples were previously passed through a 2-mm sieve to remove litter and stones, mixing the three-samples of each plot, obtaining a homogeneous sample.

Plant-cover percentage was performed following the estimation method of Agrela *et al.* (2003), using a 1 m^2 grid with 100 squares. This consists of evaluating the different cover percentages estimated in each of the squares on a scale of 0to 5, thus obtaining a value matrix, the mean of which indicated the plot cover percentage.

2.4 Statistical procedures

Analysis of variance (ANOVA) was performed in order to ascertain if differences in runoff and sediment yield existed among the different plant-cover types. The runoff, soil loss, and nutrient losses were selected for the measured variables (dependent variables), and the plant cover types were the controlled variables (independent variables). Differences between individual means were tested using the least significant difference test (LSD) at $p < 0.05$.

Irrespective of this, data from rainfall, I_{30} and EI_{30} versus runoff, eroded soil, and sediment concentration from the overall rainfall events and both assessed seasons are presented, assessing their relationship through the correlation coefficient (*r*) of each plant cover.

3. Results and discussion

3.1 Rainfall characteristics for the study period

Statistical characteristics of the rainfall depth, I_{30} and EI_{30} of the erosive rain events (with production of runoff) during the study period are shown in Table 2. Total erosive rainfall for the first and the second hydrological year was 250.4 and 410.6 mm, respectively, of which only 15 and 18 produced soil erosion. The first year was a relatively dry year, with a lower cumulative annual rainfall than the mean over the last 30 years for the area (449.0 mm), but the second year had higher rainfall.

Table 2. Statistical characteristics of rainfall for both years

	Rainfall (mm)	I_{30} (mm h^{-1})	EI_{30} (MJ mm ha^{-1} h^{-1})
Year 1			
Average	16.7 ± 9.5	2.8 ± 2.6	7.3 ± 7.9
Max.	42.8	9.1	26.9
Min.	5.0	0.3	0.5
Total	250.4	41.8	110.0
Events	15	15	15
Year 2			
Average	22.8 ± 24.9	8.4 ± 13.5	26.9 ± 49.9
Max.	107.9	58.7	215.6
Min.	4.4	0.2	0.30
Total	410.6	151.6	485.9
Events	18	18	18

I_{30}, Maximum intensity at 30 min; EI_{30}, erosivity index; ± standard deviation.

Monthly rainfall amounts were highly variable, with very dry conditions in July and August of both years and wetter months, in November (63.7 mm) of the first year and September (117.1) of the second year (Fig. 3). These rainfall events were characterized by a low mean rainfall intensity of 87 and 61% for the first and the second year, respectively, with a mean intensity < 5 mm h^{-1}; while only 0 and 22% for the first and the second year, respectively, had a mean intensity > 10 mm h^{-1}. The high variability of monthly rainfall from one year to another is reflected in the recorded data. The inter-seasonal, as well as the interannual rainfall variability is also clearly displayed (Fig. 3)

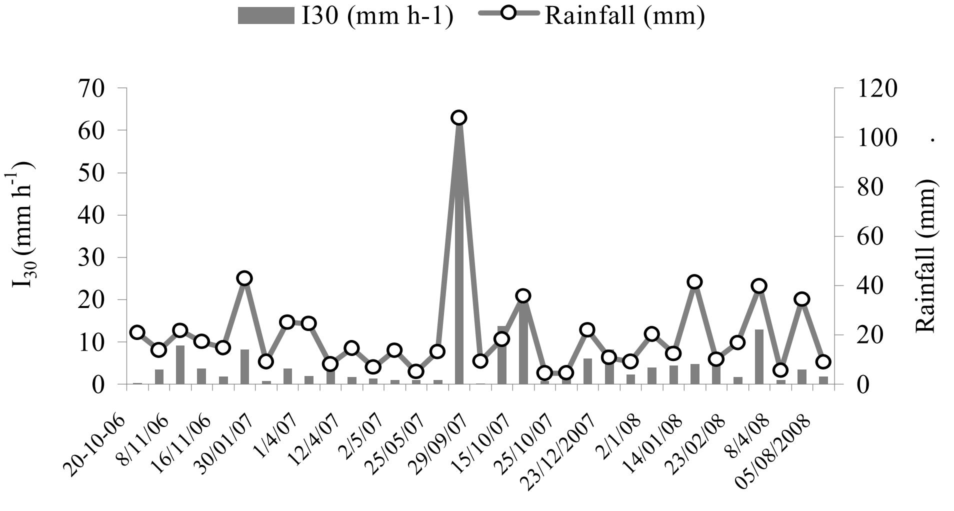

Figure 3. Amount of rainfall and I_{30} for the erosive events during the two hydrological years

3.2 Runoff and soil-erosion response

According to a comparison of the results for the yearly data, the control plot (Bs) had significantly higher rates of soil loss and runoff than the rest of the treatments with plant covers (26.4 Mg ha^{-1} and 55.7 mm yr^{-1}, respectively). The plant covers studied gave the following results in runoff: Ro > Sa > An > Th ≈ La > Sv (41.7, 38.2, 35.5, 16.9, 16.1, and 12.4 mm yr^{-1}, respectively) whereas annual soil losses gave the following trends: Sa > An > Ro > Th > Sv > La (18.0, 13.5, 13.4, 5.5, 4.4, and 3.2 Mg ha^{-1} yr^{-1}, respectively). This means that Sv reduced runoff and soil erosion with respect to Bs by 78 and 83%, respectively. On the other hand, La and Th were also very effective plant covers in reducing runoff (71 and 88%, respectively) and soil erosion with respect to Bs (70 and 79%, respectively). Our results for soil erosion on bare soil were much higher than those obtained by Bautista *et al.* (1999) in Alicante (SE, Spain) for closed erosion plots and natural rainfall (0-8 Mg ha^{-1} yr^{-1}), Castillo *et al.* (1997) and Romero Diaz et al. (1998, 2000) in Murcia (0.012-1.84 Mg ha^{-1} yr^{-1}) and by Durán et al. (2005) for the same area in bare soil (9.1 Mg ha^{-1} yr^{-1}). These high erosion rates are very common on steep sloping land with a land-use change from natural landscape to agricultural systems (Lal, 1990). Figure 4 presents the analysis of variance concerning the effect of the plant covers on the average runoff and soil erosion. The lowest soil erosion rates were recorded under Th and Sv (0.14 and 0.17 Mg ha^{-1}, respectively), which values differed significantly from the other plant covers tested.

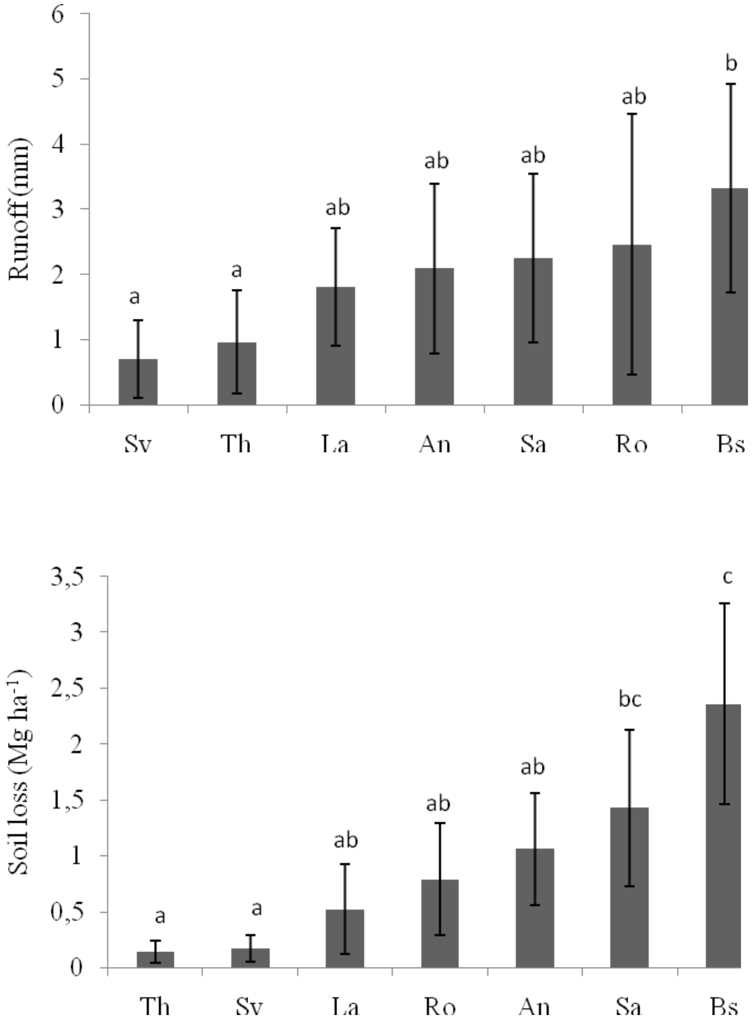

Figure 4. Mean soil erosion and runoff after a storm event for each plant treatment. Columns with different letters are statistically different at the level 0.01 (LSD). Sv, Spontaneous vegetation; Th, *Thymus mastichina*; La, *Lavandula dentata*; An, *Antyllis cytisoides*; Sa, *Satureja obovata*; Ro, *Rosmarinus officinalis*; Bs, bare soil. Vertical bars represent standard deviation (n = 33)

Bs was the treatment showing the highest erosion rates (2.36 Mg ha^{-1}). In terms of runoff, significantly lower values for Sv and Th were recorded in comparison with Bs (0.7, 0.9, and 3.3 mm, respectively). However, the rest of the plant covers (La, An, Sa, and Ro) did not significantly differ from each other (Fig. 4). The trend for runoff and for soil loss was found to be higher during the second study year, when the highest rainfall was recorded. Compared to bare soil, Th and Sv reduced the runoff with 94 and 93%, and reduced erosion with 71 and 79%, respectively. The least effective for soil erosion among the plant covers was Sa, which reduced soil loss by only 39%, and the least effective regarding to runoff was Ro, which reduced it by only by 26%, with respect to Bs (Fig. 4). In general, the plant covers softened the mechanical impact of the raindrops on the soil surface of the taluses, diminishing the superficial runoff and thereby aiding soil conservation. The importance of vegetation in erosion control is attributed to two main effects: on the one hand, the direct protection of the soil surface by the canopy and litter covers that intercept rainfall, and on the other hand the indirect improvement of the soil physical and chemical properties, essentially through the incorporation of organic matter (García-Ruíz et al., 1995; Bochet et al., 1998)

The measurements made on the erosion plots showed that in all plant covers, runoff started to occur with rains of over 5-15 mm (Fig. 5). From these data, linear relationships were established between the amount of rainfall and the runoff. A more detailed summary of the relationships among runoff, soil erosion, and rainfall parameter (rainfall depth, I_{30}, and EI_{30}) is shown in Table 3. As shown, runoff correlated better with rainfall depth than with I_{30} or EI_{30}, and in fact, for some plant covers (Sa, An, and Ro), the relationship between runoff and EI_{30} was not statistically significant. Soil erosion was more related to EI_{30} and sediment concentration in general presented less relationship with the rainfall parameters studied. The highest percentage of soil covered correlated with the lowest runoff and soil erosion rates. Fig. 6a shows the evolution of the percentage of soil covered by each type of plant during the study period and the relationship between soil erosion (Fig. 6b) and runoff (Fig. 6c) with this percentage. Sa, An, and Ro plots were the plant covers with the lowest percentage of soil covered and therefore showed the highest soil erosion and runoff rates. On the other hand, Sv, Th, and La, covered the soil more efficiently, ameliorating the production of soil erosion. This agrees with Thurow et al. (1986) and Hofman and Ries (1991), who reported that erosion rates increase with a decrease in the amount of plant cover. Therefore, native vegetation, with its greater cover, produces more biomass and, thus, augments the organic-matter content and structural stability of the soil. In this sense, Table 4 shows the average soil organic matter (SOM) percentage after 12 and 24 months of installing the plant covers. Plant covers increased SOM with time, this being higher in the Sv plot, followed by La and Th (Table 4) and lower in Sa and finally Bs plots. This low SOM content in Bs when compared with the rest of treatments was due to the easy breakdown of soil aggregates, being more exposed to soil erodibility (Fullen 1992; Fenton et al., 2005).

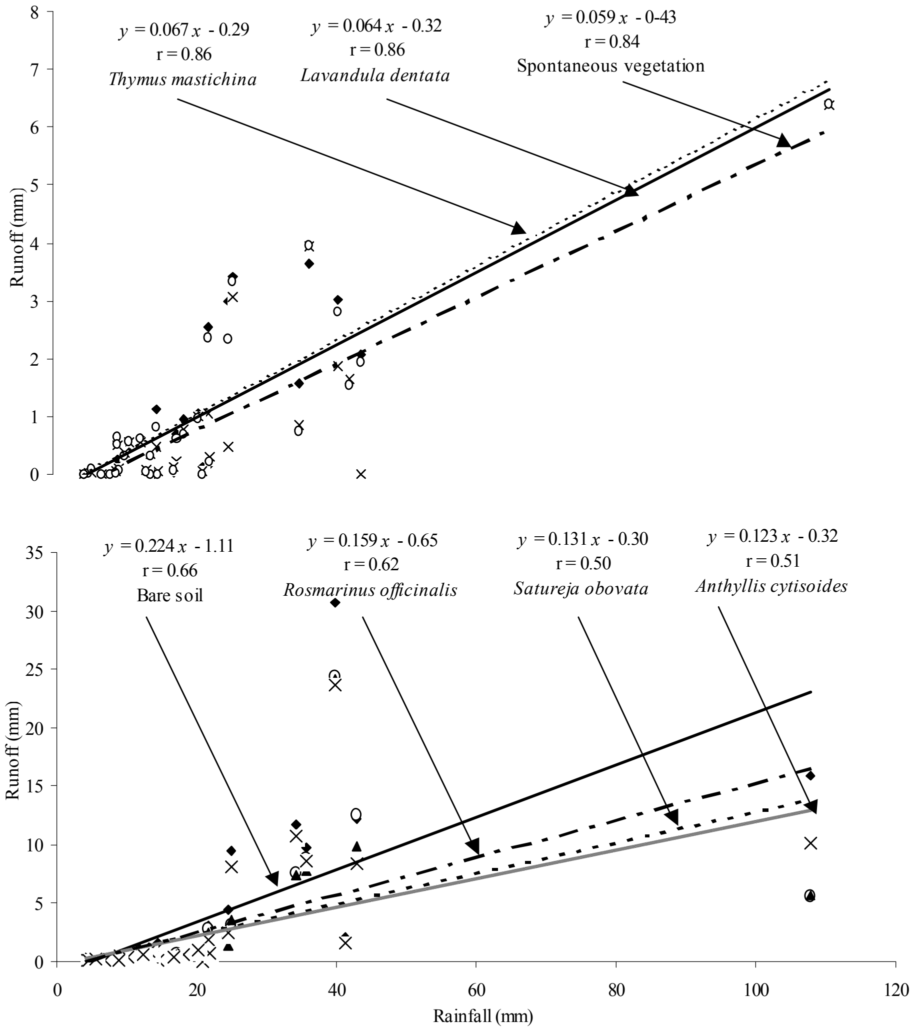

Figure 5. Rainfall (mm) versus runoff (mm) for the six plant cover treatments and the control plot (Bare soil)

Table 3. Relationship between mean runoff and soil erosion for all the treatments

	Thymus mastichina	*Lavandula dentata*	Spontaneous vegetation	Bare soil	*Satureja obovata*	*Anthyllis cytisoides*	*Rosmarinus officinalis*	All treatments
R	0.51	0.66	0.68	0.79	0.95	0.62	0.80	0.70
R^2	0.26	0.44	0.46	0.62	0.92	0.39	0.63	0.48
P	**	***	***	***	***	***	***	***
Equation	$y = 3.7 + 6.2x$	$y = -1.9 + 12x$	$y = 1.4 + 10.3x$	$y = 4.0 + 16.7x$	$y = 1.4 + 8.5x$	$y = 9.5 + 8.0x$	$y = 4.3 + 3.2x$	$y = 2.3 + 10.4x$

**, $p < 0.01$; ***, $p < 0.001$

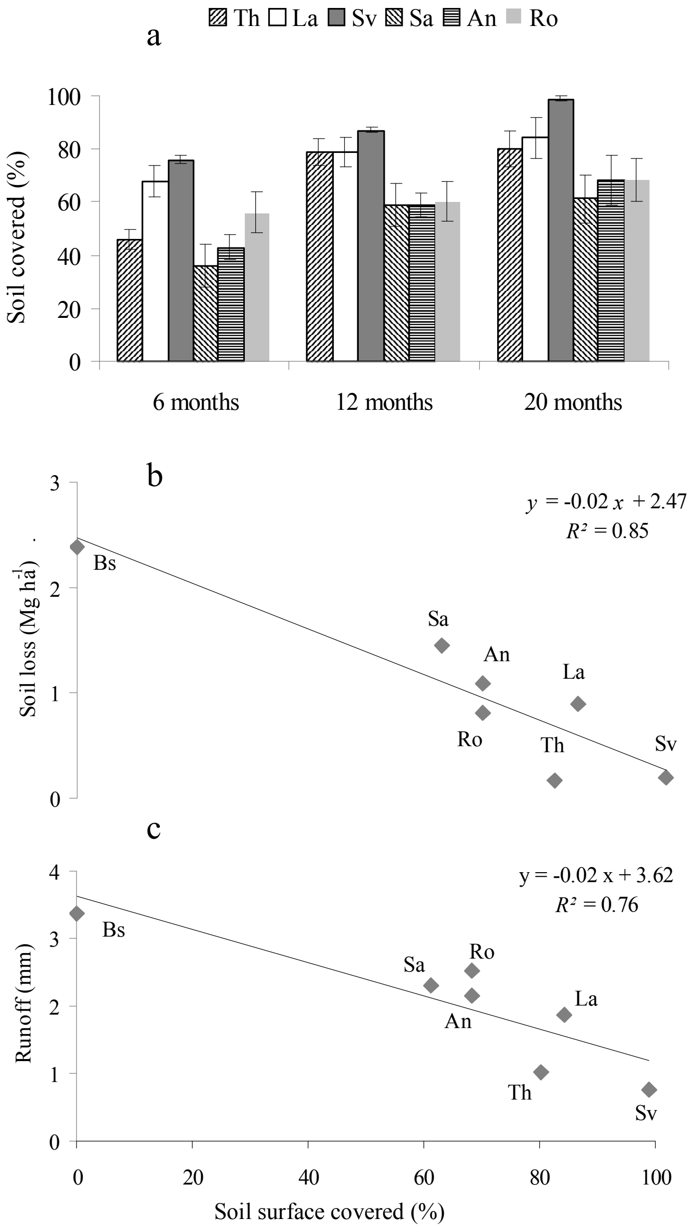

Figure 6. Soil coverage by different plant cover and its influence on soil erosion and runoff. Soil surface covered by plant covers throughout the study period (a). Relationship between soil erosion and soil surface covered (b). Relationship between runoff and soil surface covered (c)

Table 4. Average percentage of soil organic matter (0–5 cm) under each treatment

Time (months)	Th	La	Sv	Bs	Sa	An	Ro
12	1.51 (± 0.23)	1.62 (± 0.62)	1.89 (± 0.41)	0.74 (± 0.34)	1.32 (± 0.27)	1.37 (± 0.34)	1.41 (± 0.22)
24	1.52 (± 0.57)	1.63 (± 0.58)	1.98 (± 0.72)	0.63 (± 0.17)	1.30 (± 0.19)	1.41 (± 0.21)	1.48 (± 0.33)

(± Standard deviation); Th, *Thymus mastichina*, La, *Lavandula dentata*, Sv, Spontaneous vegetation; Bs, bare soil; Sa, *Satureja obovata*; An, *Anthyllis cytisoides*; Ro, *Rosmarinus officinalis*.

All plant covers provided greater soil organic matter (with a percentage increase with respect to the initial situation of 1.5, 0.7,4.7, 2.9, and 4.9% for Th, La, Sv, An, and Ro, respectively), however, there was a decrease in Sa and Bs (1.5 and 14.6% reduction with respect to the initial content, respectively). This increase of SOM and therefore soil quality as result of plant covers agrees with many other authors (Meentemeyer et al., 1982; Andreu et al., 1998; Sánchez et al., 2002; Durán et al., 2006). Therefore, the benefits from plant covers are crucial for the improvement of soil quality.

3.3 Nutrient losses control

Table 5 shows the results for the N-NO_3, N-NH_4, P-PO_4 and K losses per area by runoff and N, P and K losses per area in sediments. The greatest total N-NO_3 losses per area were recorded in Bs plot, while the lowest were measured in Th and La. The NO_3 losses decreased in the following order: Bs > Ro > An > Sa > Sv > Th > La. However, N-NH_4 followed the pattern: Bs > Sa > An > La > Ro > Sv > Th. For P-PO_4 and K, the highest losses were again recorded in Bs (Table 5). The results of the present study indicate that the Bs plot had the highest rate of nutrient losses in terms of runoff per area and the lowest were recorded in Th, Sv and La, with the exception of K, for which the lowest losses rates were found in the An and Sa plots.

In general, the transported amount of N-NH_4 per area was lower than for N-NO_3. The dominance of N-NO_3 in the three plots suggests that the dissolved nitrogen in the runoff came mainly from N fertilizers applied on the platform of the terraces for fruit cultivation, rather than from the soil, and the same applies to the dissolved NH_4^+ contained in the runoff.

Table 5. Annual nutrient losses with runoff and eroded soil under the different plant covers

Plant cover	In runoff				In sediment		
	(mg m^{-2} yr^{-1})						
	NO_3-N	NH_4-N	PO_4-P	K	N	P	K
Th	148.2	7.4	1.2	179.4	218.8	7.8	44.1
La	80.6	19.2	1.9	214.8	78.9	3.8	21.1
Sv	302.5	11.7	1.9	216.2	187.9	12.1	99.3
Sa	312.8	40.0	2.5	114.3	796.0	19.9	63.7
An	334.5	24.5	3.6	106.3	778.0	17.0	34.9
Ro	366.2	17.6	3.1	227.6	528.0	15.8	52.9
Bs	367.8	44.1	4.0	289.2	1,025.4	34.8	100.5

Th, *Thymus mastichina*, La, *Lavandula dentata*, Sv, Spontaneous vegetation; Bs, bare soil; Sa, *Satureja obovata*; An, *Anthyllis cytisoides*; Ro, *Rosmarinus officinalis*.

Our results for N-NO_3 annual losses from bare soil were higher than those recorded by Durán et al. (2004) for similar conditions (probably due to the more aggressive rainfall events registered in this experiment), and much lower than those reported by Ramos and Martínez-Casasnovas (2006) in vineyards. On the contrary, P-PO_4 losses recorded in this experiment (from 0.012 to 0.040 kg ha^{-1} yr^{-1} for Th and Sv plots, respectively) were similar to those found by Durán et al. (2006), who reported rates from 0.07 to 0.29 kg ha^{-1} yr^{-1} in olive orchards under different land management and to those of Ramos and Martínez-Casasnovas (2006). K losses in runoff ranged from 106.3 to 289.2 mg m^{-2} yr^{-1} for An and Bs, respectively (Table 5) and from 21.1 to 100.5 mg m^{-2} yr^{-1} for La and Bs, respectively in sediments. These K losses rates were lower than those reported by Durán et al. (2006) in olive orchards (47.0-333.8 mg m^{-2} yr^{-1}). This appreciable amount of dissolved potassium resulted in K-rich runoff, and came presumably from K fertilizers (K_2SO_4, KH_2PO_4, KCl and KNO_3) used for fruit production. Total nutrient losses in agricultural systems may be affected by various factors: soil use and the forms of P and the hydrological processes controlling transport as well as rainfall characteristics (Edwards and Daniels, 1993; Schroeder et al., 2004). Bare-soil plots produced the highest nutrient losses, which are diminished by the use of plant covers, most effectively by La, Sv and Th, except for K-losses, that showed the highest decrease in An, Sa and Th plots.

3.4 Nutrient concentration in runoff

The average N-NO_3 concentration in the runoff ranged from 4.9 to 24.3 mg L^{-1} for La and Sv, respectively, and showed the following order for the respective plant covers: Sv > Ro > An > Bs > Sa > Th > La (Table 6).

Table 6. Nutrient concentration in the runoff for the different plant covers

Plant cover	N-NO_3	N-NH_4	P-PO_4	K
		(mg L^{-1})		
Th	8.9 ± 10.0	0.4 ± 0.4	0.06 ± 0.05	10.9 ± 11.4
	(29.1)	(1.4)	(0.15)	(43.3)
La	4.5 ± 6.1	1.8 ± 1.7	0.20 ± 0.21	28.7 ± 33.7
	(24.1)	(4.7)	(0.71)	(130.0)
Sv	24.3 ± 19.3	1.6 ± 2.4	0.09 ± 0.05	24.1 ± 14.5
	(69.3)	(7.8)	(0.17)	(56.0)
Sa	9.6 ± 6.6	0.5 ± 0.4	0.09 ± 0.03	5.8 ± 4.9
	(22.5)	(1.7)	(0.23)	(21.3)
An	11.2 ± 8.4	0.9 ± 0.9	0.10 ± 0.06	5.2 ± 4.6
	(29.8)	(3.4)	(0.27)	(22.0)
Ro	11.8 ± 7.8	0.8 ± 1.2	0.07 ± 0.03	12.6 ± 8.4
	(29.4)	(5.2)	(0.11)	(34.0)
Bs	10.5 ± 12.9	1.5 ± 1.8	0.09 ± 0.05	12.7 ± 10.8
	(49.3)	(6.3)	(0.20)	(35.0)

Average ± standard deviation (maximum value); n = 33. Th, *Thymus mastichina*, La, *Lavandula dentata*, Sv, Spontaneous vegetation; Bs, bare soil; Sa, *Satureja obovata*; An, *Anthyllis cytisoides*; Ro, *Rosmarinus officinalis*.

The maximum concentration rates detected for a storm event exceeded 50 mg L^{-1} in Sv, which is the permissible limit for drinking water according to the WHO (2007). However, in most of the events, runoff N-NO_3 concentrations exceeded the 10 mg L^{-1}, being the upper limit recommended for drinking water by the U.S. EPA (1976). In addition, in most of the events recorded for Sv, the concentration was within the class 20-50 mg L^{-1}, which is a high enough concentration to indicate the influence of human activities, according to Spalding and Exner

(1993). Average N-NH_4 concentrations in runoff ranged from 0.43 to 1.60 mg L^{-1} for Th and Sv, respectively, exceeding 0.5 mg L^{-1}in most of the erosive events and for all the plant covers, this concentration being standard for public supplies (Huetter, 1992). Average P-PO_4 concentrations in the runoff ranged from 0.05 to 0.20 mg L^{-1}, the highest average value being reached in La and An, and the lowest in Th (Table 6). In most of the events and for all the treatments, the concentration exceeded established limits usually associated with the eutrophication of surface waters: from 0.01 mg P L^{-1} (Vollenweider, 1968; Vollenweider and Kerekes, 1980) to 0.05 mg L^{-1} (U.S. EPA, 1976).

The highest average K concentrations were registered in La, Sv, and Ro (Table 6) and the lowest in Sa and An plots. The upper limit recommended for drinking water of 12 mg L^{-1} (Griffioen, 2001) was exceeded for all the plant covers studied. K concentrations were relatively high because this element is relatively mobile and, although K does not directly result in eutrophication, the impact and risk as a potential pollutant when applied as fertilizer should be taken into account. The excessive use of K fertilizers (K_2SO_4 and KNO_3) for improvement of subtropical fruit quality is a potential source of pollution (Shinde *et al*. 2006).

3.5 Control of carbon losses

Table 7 shows the total amount of organic carbon lost by sediments per year. In general, our results for carbon losses are low due to the low content of organic matter in this soil. During the second study year, carbon losses were higher than in the first year. During the first year, total carbon losses by sediments followed the pattern: Bs > Sa > Th > Sv > Ro > La > An. Bs registered the greatest carbon losses (202.5 kg ha^{-1}), and An the least (55.4 kg ha^{-1}) (Table 7). During the second year this trend changed: Bs > Ro > Sa > An > La > Sv > Th. The Bs and Ro plots showed the heaviest carbon losses (829.9 and 652.1 kg ha^{-1}, respectively). The lightest carbon losses were measured in La, Sv, and Th plots (145.2, 140.3, and 109.3 kg ha^{-1}, respectively). Therefore, An and La plots reduced carbon losses by 73 and 69%, respectively, with respect to Bs carbon losses during the first year. Similarly, for the second year, Th, Sv, and La plots reduced carbon losses in a 89, 85, and 85%, respectively with respect to Bs plot.

Table 7. Annual organic-carbon losses by sediments and eroded soil during the study period

	In sediment *	In eroded soil (kg ha^{-1})	Total
Year 1			
Th	47.2	51.0	98.2
La	34.4	28.4	62.8
Sv	6.3	70.3	76.6
Sa	69.7	51.2	120.9
An	27.3	28.7	56.0
Ro	29.1	33.9	63.0
Bs	79.6	123.1	202.7
Year 2			
Th	45.2	64.0	109.2
La	74.1	71.6	145.7
Sv	5.0	90.4	95.4
Sa	445.9	95.9	541.8
An	332.7	97.0	429.7
Ro	652.1	115.6	767.7
Bs	829.9	130.3	960.2

*in the suspended sediment runoff. Th, *Thymus mastichina*, La, *Lavandula dentata*, Sv, spontaneous vegetation; Bs, bare soil; Sa, *Satureja obovata*; An, *Anthyllis cytisoides*; Ro, *Rosmarinus officinalis.*

Carbon losses in runoff ranged from 5.0 to 829.9 kg ha^{-1} for Sv and Bs plots (both values for the second year). These results are lower than those found by Bertol et al. (2005) for soybean and oats, who reported 16, 36, 152, and 1,779.9 kg ha^{-1} for non-tillage, minimum tillage, conventional tillage and bare soil, respectively but much higher than those recorded by Dos Santos et al. (2007), reporting from 0.2 to 55 kg ha^{-1} for different soil-management systems in semiarid environments. It is well known that organic matter is one of the first particles of the soil to be removed by water erosion, not only because of its higher concentration in soil surface but also for its low density (Barrows and Kilmer, 1963). Thus, protection of the soil surface against organic-carbon losses by sediment is feasible by using plants covers, this being one of the most effective conservation practices in these subtropical agroecosystems

3.6 Heavy-metal transport by runoff and its control

The heavy-metal concentrations in runoff collected during the two agricultural seasons varied greatly (Table 8). The concentrations of Cd and Pb were generally low. Mn concentrations ranged from 0.1 to 3,723.1 µg L^{-1} with an average concentration ranging from 170.9 to 384.1 µg L^{-1}, for An and Sv, respectively. In this sense, concentrations of Mn greatly exceeded 50 µg L^{-1}, which is the tolerance limit for drinking water (U.S. EPA, 1976). Average Cr concentrations ranged from 0.8 to 9.0 µg L^{-1} for Ro and Sa plots, respectively. The highest concentration values ranged from 5.3 to 175.5 µg L^{-1}. The Cr concentrations were lower than the drinking-water standard (100 µg L^{-1}), except for one event in Sa plot. Average Co concentrations ranged from 0.8 to 5.5 µg L^{-1} for Ro and Sa, respectively, with peaks of 5.3 to 70.7 µg L^{-1} for Ro and Sa, respectively, exceeding the 2.8 µg L^{-1}, which is the limit of Co for soil water (NMHPPE, 1998) (Table 8). Cd concentrations ranged from 0.0 to 12 µg L^{-1} for Ro and Sa, respectively, with a high peak of 282.5 µg L^{-1} for a storm event in the Sa plot. In most of the events Cd concentrations were within the 5 µg L^{-1} standard for drinking water (Stewart *et al.*, 2001), except for Sa plot. Average Ni concentrations were from 2.4 to 20.4 µg L^{-1} for Bs and La plots, respectively, with the highest peaks detected again for the Sa and La plots. The concentrations exceeded the 100 µg L^{-1} (drinking-water standard; Stewart *et al.*, 2001) but not the 1400 µg L^{-1}, which is the established limit for surface waters according to the U.S. EPA (1976) for Ni. Average Cu concentrations ranged from 4.8 to 78.2 µg L^{-1} for Th and Sa plots, respectively and the maximum concentrations were again recorded in Sa (1,706.6 µg L^{-1}). For most events, concentrations did not surpass 280 µg L^{-1}, the highest value of Cu found in a published assessment of natural surface waters of the USA (Manahan, 1991) or the 1000 µg L^{-1}, a limit value for Cu in drinking water (U.S. Public Health Service, 1962). In the same way, concentrations were lower than 100 µg L^{-1} (maximum permissible limit for drinking water, according to the Spanish Ministry of Health (BOE 20/9/90). The Cu concentrations were similar to those reported by He *et al.* (2004) for several runoff samples collected from agricultural lands (0.00-1,475 µg L^{-1}). Average Zn concentrations ranged from 1,300.8 to 3,820.9 µg L^{-1} and the highest peaks were found in the Sa and La plots (20,446.7 and 11,600.0 µg L^{-1}, respectively). Our results are much higher than those of He *et al.* (2004) for agricultural lands (0.0-1,401.0 µg L^{-1}) and, after some events, concentrations exceeded 5,000 µg L^{-1}, the maximum permitted for drinking water (Manahan, 1991). These high values for Zn concentrations may be due to the heavy Zn applications for foliar deficiencies in mango orchards and also probably from the material of galvanized sheets from the erosion plots themselves. Pb ranged from 0.1 to 1.5 µg L^{-1} and peaks were again recorded in Sa (28.8 µg L^{-}

^{1}) (Table 8). Pb concentrations in the Sa plot exceeded 15 µg L^{-1}, which is the standard for drinking water (Stewart et al., 2001) but were below 50 µg L^{-1}, the standard limit for drinking water according to Spanish Ministry of Health (BOE 20/9/90). Our Pb concentrations were very similar to those found by He et al. (2004) for different agricultural fields.

Heavy-metal losses per area are shown in Table 9. The greatest losses were recorded for Zn and the least for Ni, Mo, Cd, and Pb. For each element, the heaviest losses were recorded in the Sa and Bs plots, and the lowest in Th, La, and Sv. The Sv cover reduced Mn, Ni, Mo, Cu, and Zn losses by 52, 69, 71, 82, and 76%, respectively, compared to Bs. Among aromatic medicinal plant covers, Th had the lowest heavy-metal losses per area, except for Mn and Zn, for which the La plot was the lowest. Therefore, plant covers play an important role in controlling heavy-metal pollution risk, decreasing pollutant transport by runoff in comparison to bare soil.

Table 8. Heavy-metal concentration in runoff from the different erosion plots

	Mn							Cr							Co						
											(μg L^{-1})										
	Th	La	Sv	Bs	Sa	An	Ro	Th	La	Sv	Bs	Sa	An	Ro	Th	La	Sv	Bs	Sa	An	Ro
Average	305.9	224.1	384.1	179.3	307.19	170.9	192.8	1.5	2.2	3.0	2.4	9.0	1.8	0.8	4.5	5.1	4.5	3.8	5.5	3.3	0.8
SD	596.0	287.5	855.1	425.0	837.79	318.4	447.2	2.0	2.7	5.1	4.5	35.9	3.5	1.3	4.8	6.1	5.6	5.6	14.6	5.2	1.3
Max.	2454.8	1112.6	3723.1	1889.8	3634.82	1237.8	1908.9	6.57	10.0	14.8	14.8	175.7	13.8	5.3	15.8	22.0	17.3	17.3	70.7	19.8	5.3
Min.	0.4	2.2	0.2	1.06	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0
	Ni							Cu							Zn						
Average	4.1	20.4	2.8	2.4	11.2	3.5	2.9	4.8	6.4	5.6	7.2	78.2	6.6	5.3	3694.6	3820.9	1533.9	1421.0	3009.7	2289.6	1300.8
SD	7.6	78.8	3.1	2.2	41.5	5.7	7.6	3.3	5.0	5.3	6.3	348.7	4.8	3.2	3954.5	3610.5	1784.1	1087.1	4597.9	2118.2	1090.3
Max.	31.8	355.3	9.4	9.4	203.5	25.6	38.2	15.1	22.2	17.2	24.0	1706.3	19.8	12.6	10006.0	11600.0	5768.2	3966.5	20446.7	7979.9	4236.5
Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3	0.0	0.5	0.2	0.8	1.2	6.7	27.2	0.0	2.7	2.2	6.3	1.9
	Mo							Cd							Pb						
Average	2.5	2.6	3.4	2.5	3.4	3.0	3.2	0.1	0.2	0.0	0.1	12.0	0.1	0.0	0.6	0.7	0.5	0.4	1.5	0.2	0.1
SD	3.2	1.6	2.6	2.2	3.8	3.0	2.6	0.2	0.9	0.0	0.3	57.6	0.1	0.0	0.7	1.2	1.1	0.7	6.0	0.7	0.4
Max.	12.8	6.3	8.0	7.8	18.8	14.2	10.2	0.9	4.1	0.1	1.5	282.5	0.2	0.1	2.0	3.5	4.0	2.7	28.8	2.7	1.8
Min.	0.6	0.6	0.5	0.1	0.6	0.7	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

SD, standard deviation; Th, *Thymus mastichina*, La, *Lavandula dentata*, Sv, spontaneous vegetation; Bs, bare soil; Sa, *Satureja obovata*; An, *Anthyllis cytisoides*; Ro, *Rosmarinus officinalis*.

Table 9. Average annual heavy-metal losses per unit area for the different plant cover

	Plant cover						
	Th	La	Sv	Sa	An	Ro	Bs
				(mg m^{-2} yr^{-1})			
Mn	5.2	3.6	4.8	11.7	6.1	8.0	10.0
	(± 1.2)	(± 2.9)	(± 3.2)	(± 9.1)	(± 5.9)	(± 5.8)	(± 6.7)
Ni	0.07	0.33	0.04	0.43	0.12	0.12	0.13
	(± 0.01)	(± 0.21)	(± 0.03)	(± 0.56)	(± 0.08)	(± 0.09)	(± 0.22)
Mo	0.04	0.04	0.04	0.13	0.11	0.13	0.14
	(± 0.03)	(± 0.03)	(± 0.03)	(± 0.09)	(± 0.08)	(± 0.08)	(± 0.13)
Cr	0.02	0.04	0.04	0.34	0.06	0.03	0.13
	(± 0.03)	(± 0.02)	(± 0.03)	(± 0.23)	(± 0.05)	(± 0.02)	(± 0.17)
Cu	0.08	0.10	0.07	2.98	0.23	0.22	0.40
	(± 0.05)	(± 0.08)	(± 0.05)	(± 1.9)	(± 0.19)	(± 0.19)	(± 0.38)
Cd	0.00	0.00	0.01	0.02	0.00	0.00	0.01
	(± 0.00)	(± 0.00)	(± 0.01)	(± 0.01)	(± 0.00)	(± 0.00)	(± 0.01)
Co	0.08	0.08	0.06	0.21	0.12	0.08	0.21
	(± 0.06)	(± 0.05)	(± 0.07)	(± 0.32)	(± 0.09)	(± 0.03)	(± 0.26)
Zn	62.7	61.4	19.0	80.6	81.2	54.2	79.2
	(± 46.8)	(± 39.8)	(± 21.0)	(± 67.1)	(± 78.3)	(± 45.7)	(± 89.1)
Pb	0.01	0.01	0.01	0.03	0.01	0.01	0.02
	(± 0.0)	(± 0.0)	(± 0.02)	(± 0.02)	(± 0.02)	(± 0.01)	(± 0.03)

(± standard deviation); Th, *Thymus mastichina*, La, *Lavandula dentata*, Sv, spontaneous vegetation; Bs, bare soil; Sa, *Satureja obovata*; An, *Anthyllis cytisoides*; Ro, *Rosmarinus officinalis.*

4. Conclusions

The results of this research are in line with the findings of other studies, demonstrating the capacity of plant covers to reduce soil erosion and surface runoff on agricultural land. In this context, in our study, the average annual soil erosion rate was 55.8, 41.7, 38.2, 35.5, 16.9, 16.1, and 12.4 Mg ha^{-1} yr^{-1} for Bs, Ro, Sa, An, Th, La, and Sv, and the annual runoff, 26.4, 18.0, 13.5, 13.4, 5.5, 4.4, and 3.2 mm, respectively. Thus, the implementation of aromatic plant covers in the taluses of subtropical orchard terraces substantially reduced soil erosion and runoff. Similarly, nutrient losses were reduced by using plant covers in comparison to the bare soil treatment, especially in the Th, Sv, and La plots. In the same way, carbon losses by erosion were significantly reduced by the use of plant covers and at the same time, SOM was increased, due to the greater litter fall and nutrient cycling (Rodríguez et al., 2009c)

Under semi-arid conditions, where rainfall is not only responsible for the soil degradation but is also the main factor determining yields in subtropical agroecosystems, efforts need to be continued to develop sustainable systems for agriculture acceptable by the local farmers. In this context, the alternative cultivation of aromatic plant covers, such as thyme or lavender, could represent extra income for farmers and an environment-friendly measure that increases the stability of the taluses of the orchard terraces and helps minimize the risk of pollution by agricultural runoff.

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Capítulo III

Litter decomposition and nitrogen release in a sloping Mediterranean subtropical agroecosystem on the coast of Granada (SE, Spain): effects of floristic and topographic alteration on the slope

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Litter decomposition and nitrogen release in a sloping Mediterranean subtropical agroecosystem on the coast of Granada (SE, Spain): effects of floristic and topographic alteration on the slope

Rodríguez Pleguezuelo, C.R.[a,*], Durán Zuazo, V.H.[a,b], Martín Peinado, F.J.[c], Franco Tarifa, D.[d]

[a] IFAPA Centro Camino de Purchil. Aptdo. 2027; 18080 Granada, Spain.
Phone: (+34) 958 895 255; (+34) 647 199 854. Fax: (+34) 958 895 202;
*corresponding author email: *crocio.rodriguez@juntadeandalucia.es*
[b] IFAPA Centro Las Torres-Tomejil. Crtra Sevilla-Cazalla, km 12.2; 41200 Alcalá del Rio (Sevilla) Spain.
[c] Departamento de Edafología y Química Agrícola, Universidad de Granada, C/Severo Ochoa s/n, 18071-Granada, Spain
[d] Finca "El Zahorí". Patronato de Cultivos Subtropicales Plaza de la Constitución 1, Almuñécar (Granada), Spain

ABSTRACT

On the coast of Granada (SE Spain), an economically important area for subtropical fruit cultivation, the crops are grown on orchard terraces. Also, high amounts of fertilizers, often excessive, are used in this type of intensive agriculture. However, each year significant fractions of nutrients taken up by the trees return to the soil by fallen leaves. Using a litter-bag technique, we assessed the decomposition rates and N release in various types of litter. Our main purpose was to compare two different agroecosystem scenarios: (1) an unaltered slope consisting mainly of a mixture of herbaceous plants (*Papaver rhoeas*, *Convolvulus* sp., *Malva sylvestris*, *Reseda phyteuma*, *Anacyclus* sp., *Sinapis arvensis*, *Medicago* sp.) among spontaneous perennial woody shrubs (*Genista umbellata*, *Olea europaea*, *Lavandula officinalis*, *Phlomis purpurea*, *Retama sphaerocarpa*), and (2) an altered slope cultivated with subtropical trees on terraces: loquat (*Eriobotrya japonica)*, mango (*Mangifera indica)*, avocado (*Persea americana)*, and cherimoya (*Annona cherimola*), with groundcover plantings of aromatic, medicinal, and melliferous plants (AMMPs) on the taluses of the terraces, which are usually used for erosion control: *Lavandula dentata*, *Thymus mastichina*, *Satureja obovata*, *Rosmarinus officinalis*, *Anthyllis cytisoides*. In the leaves from the subtropical crops, we found the highest decomposition rates in cherimoya and the lowest in mango (1.30 and 0.64 years^{-1}, respectively). Leaves from mango and loquat registered initial peaks of N immobilization and later N release, which was highest in cherimoya and avocado leaves (71.2 and 56.8% of the initial remaining N). In the spontaneous woody shrubs, *Olea europaea* and *Genista umbellata* were the slowest in decomposing (1.18 and 1.01 years^{-1}, respectively) contrary to *Lavandula officinalis*, which decomposed fastest (2.22 years^{-1}). Only *Lavandula officinalis* and *Phlomis purpurea* registered a net N release at the end of the study. The AMMPs showed different decomposition patterns: *Lavandula dentata* registered the highest decomposition rates and *Rosmarinus* the lowest (1.9 and 1.1 years^{-1}, respectively). *Thymus mastichina*, *Lavandula dentata*, and *Satureja obovata* had the highest N-release, whereas *R. officinalis* and *A. cytisoides* showed N immobilization (183 and 122% of the initial N). Knowledge of the dynamics of nutrient release and litter decomposition will be useful for predicting nutrient availability and nutrient cycles in these types of agroecosystems where subtropical orchards are grown on terraces.

Keywords: nitrogen cycling, terrace agriculture, subtropical crops, litter decomposition.

1. Introduction

Decomposition of plant litter refers to the physical and chemical processes involved in reducing litter to its elemental chemical constituents. As such, it is a major determinant of the nutrient cycles of most terrestrial ecosystems (Meentemeyer 1978; Swift and Anderson 1989; Van Vuuren et al., 1993; Aerts and De Caluwe, 1997). In this sense, nutrient release from decomposing litter affects primary productivity in ecosystems (Blair, 1988), since these nutrients become available for plant uptake and are not lost from the system (Santa Regina et al., 1997). Moreover, decomposition of plant litter plays an important role in carbon fluxes of terrestrial ecosystems (Couteaux et al., 1995; Sun et al., 2004). In general terms, litter-decomposition rates are controlled by environmental conditions, the chemical composition of the litter, and by soil organisms. It has been postulated that these factors exert a hierarchically organized control on litter decomposition due to the regulation of microbial activity at decreasing scales of time and space. That is, there are three main levels of litter-decomposition control, which operate in the following order: climate > litter chemistry > soil organisms (Lavelle et al., 1993). Climate directly influences litter decomposition through temperature and moisture; however, climate can also have an indirect effect on litter chemistry through influence on plant-community composition and litter quality, determining litter potential decomposition (Lavelle et al., 1993; Pérez et al., 2007). In terms of the chemical composition and quality of organic matter, three main fractions can be distinguished: the first is the easily soluble fraction, which can be very quickly lost; the second is a non-soluble but easily degradable fraction, and is composed mainly of hemicellulose and cellulose; and the third, which lasts much longer, is composed of lipids, lignins, and lignified carbohydrates (Heal et al., 1997). Many researchers have demonstrated relationships between these initial litter-quality characteristics and decomposition rates for a large number of plant species (e.g. Meentemeyer, 1978; Berg and Staaf, 1980; Sariyildiz and Anderson, 2003). In this sense, the carbon-nitrogen ratio (C:N) has been demonstrated to be a good index of the susceptibility of litter to be degraded (Berg et al., 1982; Taylor et al., 1989). In general, litter with a low C:N ratio is decomposed faster than litter with a high C:N ratio (Adams and Atwill 1982). However, when C:N ratios exceed 75-100, other indexes such as lignin:N may be better (Heal et al., 1997).

Litter decomposition is a process which has been widely studied in several major ecosystems: tropical and subtropical climates (Heneghan et al., 1998; Pandey et al., 2007), semiarid (Tateno et al., 2007), temperate (Cookson et al., 2007; Lensing and Wilse, 2007), and Mediterranean (Moro and Domingo 2000; Martins et al., 2006; Sirulnik et al., 2007). However, while extensive research on litter decomposition and nutrient release has been conducted in forest ecosystems (Guo and Sims, 1999; Magill and Aber, 1998; Teklay and Malmer, 2004) and for several debris types from agricultural crops (Chaves et al., 2004; Quemada and Cabrera, 1995), the process of decomposition of litter in orchard systems and the dynamics of nutrient release have received little or no attention. For instance, there is no information available on the use of mango for mulch, litter or compost (Musovoto et al., 2000).

In the Mediterranean region, and particularly in arid and semiarid areas of south-eastern Spain, soil degradation is a serious problem, due to anthropic activities together with long periods of drought followed by intense and irregular rainfall. One of the most significant causes of soil degradation is the removal of native vegetation. When plants are removed, natural C and N cycles are disrupted and the organic-C of the soil is reduced, and thus restoration of the resident vegetation is the most effective way of regenerating soil health. Shrubs, the most widely represented plant form in the degraded Mediterranean ecosystem receive particular attention in this study. It is well known that they promote a resistant soil cover and are able to reduce erosion. Furthermore, some of them, woody legumes, have proved to be competitive in arid environments and to improve fertility by transferring N to the soil-plant system (Barea et al., 1992; Rode, 1995; Geesing et al., 2000). Since N is the most easily lost soil nutrient, it can become the limiting factor in recovering and protecting soils (Kirschbaum, 2001).

In this study, we investigated the decomposition of 15 types of leaf-litter plants. The main objective was to compare the decomposition rates and nitrogen cycling of the predominant species from two different sloped ecosystems in the area: on the one hand, the altered-ecosystem slope (AES), which consists of the cultivation of tropical and subtropical crops in orchard terraces. The trees cultivated in the area are: avocado (*Persea americana* Mill.), mango (*Mangifera indica* L.), loquat (*Eriobotrya japonica* Lindl.), cherimoya (*Annona cherimola* Mill.) (Durán et al., 2003, 2006; Durán and Rodríguez, 2008; Rodriguez et al., 2009). Also, as a measure of erosion and runoff control, aromatic, medicinal, and melliferous plants were planted on the taluses of these terraces, and were also studied: *Lavandula dentata*, *Thymus mastichina*, *Satureja obovata*, *Rosmarinus officinalis*, and *Anthyllis cytisoides*. On the other hand, we also monitored the unaltered-ecosystem slope (UES), where, mixed with herbaceous annuals and biannuals, different woody and annual and perennial plants prevail: *Genista umbellata*, *Olea europaea*, *Lavandula officinalis*, *Phlomis purpurea*, *Retama sphaerocarpa*.

The main objective of the present study was to compare the litter decomposition rates and nitrogen recycles between two ecosystems: altered slopes with agricultural purposes (AES) and unaltered slopes with native vegetation (UES).

2. Materials and methods

2.1. Site description

The study was carried out at the experimental farm "El Zahorí" in Almuñécar, Granada (SE Spain) (36º 48´00´´N, 3º 38´0´´W) and at an elevation of 180 m a.s.l. (Fig. 1). Local temperatures are subtropical to semi-hot within the Mediterranean subtropical climatic category (Elias and Ruiz, 1977). The average annual rainfall in the study zone is 449.0 mm with a mean annual temperature of 20.8ºC.

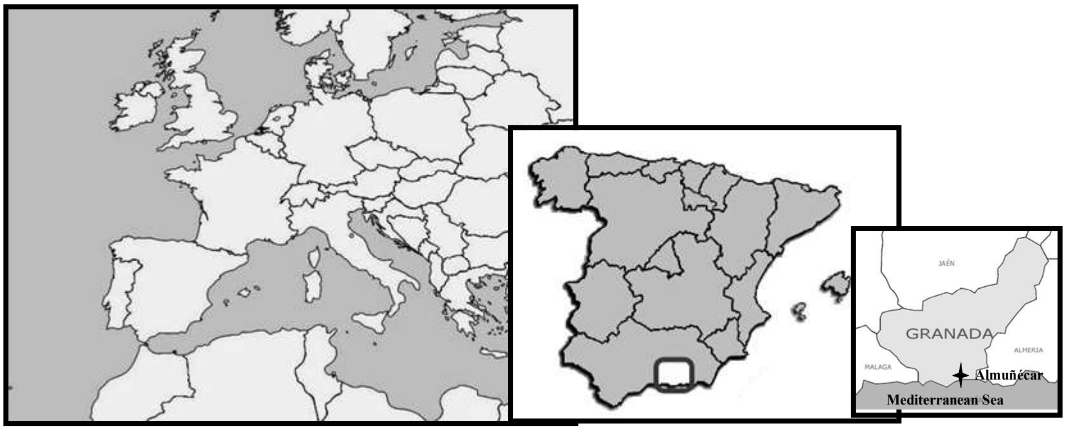

Figure 1. Location of the study area in south-eastern Spain (Almuñécar, Granada).

The soils, formed from weathered slates, vary in depth, and some are rocky, providing generally very good drainage, especially in the fill used to construct the platforms of the terraces. The soils of the zone are Typic Xerorthent (Soil Survey Staff, 1999) and Eutric Regosol (FAO, 1998) with 684 g Kg^{-1} of sand, 235 g Kg^{-1} of silt, and 81 g Kg^{-1} of clay, plus 9.4 g Kg^{-1} of organic matter, as well as 0.7 g kg^{-1} of N, 14.6 mg kg^{-1} P, and 178.7 mg kg^{-1} assimilable K.

2.2. Litter-bag technique and plants

In this study, we used the litter-bag technique because it represents the most standardized method for studying litter decay (Aerts, 1997). Therefore, the litter-bag technique using a nylon mesh bag (Bocock and Gilbert, 1957) was used to quantify leaf-litter decomposition. A certain amount of fresh plant was harvested; each plot occupied 25 m^2, which is the minimum area for collecting shrubs (Barkman, 1989). Leaves from subtropical trees were taken from the middle part of the canopy, following the cardinal points and from normal shoots of similar physiological age. The bags were 24 cm x 15 cm x 1 mm mesh for the AMMPs and natural spontaneous shrubs, and 50 cm x 25 cm x 1 mm mesh for leaves from subtropical crops. Mesh size was always 1 mm, small enough to prevent major losses of the smallest leaves, yet large enough to permit aerobic microbial activity and free entry of small soil animals (e.g. earthworms, termites, etc. are excluded from decomposition; Dutta and Agrawal, 2001).

Fresh mature leaves from the different experimental groups of vegetation were included in litter bags for their study. The aromatic, medicinal, and melliferous plants (AMMPs), which were also used for erosion and runoff control in the taluses of orchard terraces in AES (Rodríguez et al., 2009) included: *Thymus mastichina* L., *Lavandula dentata* L., *Satureja ovovata* Lag., *Anthyllis cytisoides* L., and *Rosmarinus officinalis* L. cv *postratum*. The local subtropical crop leaves were from orchards of: a 15-year-old avocado (*Persea americana* Mill.), 16-year-old mango (*Mangifera indica* L.), 17-years-old cherimoya (*Annona cherimola* Mill.), and 12-years-old loquat (*Eriobotrya japonica* Lindl.). AMMPs and subtropical crops represented the altered-ecosystem slope (AES). A mixture of annual herbaceous plants (AHPs) growing in the area from UES, predominantly *Papaver rhoeas*, *Convolvulus* sp., *Reseda phyteuma*, *Anacyclus* sp., *Sinapis arvensis*, *Medicago* sp., *Poa annua*, and *Malva sylvestris.* These species were collected randomly in a 50 cm x 50 cm quadrat. The most representative natural spontaneous shrubs consisted of *Retama sphaerocarpa* L., *Lavandula officinalis* Chaix, *Genista umbellata* L'her, *Olea europaea* cv. *sylvestris,* and *Phlomis purpurea* L. These spontaneous woody shrubs and the mixture of annual herbaceous plants represented the vegetation growing on the unaltered-ecosystem slope (UES).

Litter-bag experiments were conducted for a minimum of 12 months. For each type of vegetation, 24-36 bags were buried at the beginning (at 10-15 cm in depth) and recovered regularly after a minimum period of 2 months. At each recovery, 6-10 litter bags were collected for each type of vegetation. The experiments, made between May 2006 and October 2008, are summarized in Table 1.

2.3. Measurements, laboratory methods, and statistical analyses

When the buried bags were retrieved from the soil, the adhering soil, plant detritus and the "ingrowth" roots were removed. The bags were carefully brushed and washed using tap water followed by distilled water and then dried at 70ºC to constant weight and weighed for the determination of remaining biomass. The loss of mass over time was expressed with the exponential decay model:

$$W_t = W_o\, e^{-kt} \qquad \text{(Eq. 1)}$$

Table 1. Details of the experimental study

System	Plant type	Total time (months)	Minimum recovery time (months)	Number of retrievals	Bags at each retrieval	Total bags for each plant type
UES	AHPs	12	3	4	6	24
UES	RS, LO, GU, OE, PP	12	2	6	6	36
AES	SO, AC, RO	14	2	4	8	32
AES	PA, MI, ACh, EJ	18	2	3	8	24
AES	TM, LD	12	3	4	6	24

UES, Unaltered ecosystem slope; AES, altered ecosystem slope; AHPs annual herbaceous plants; RS, *Retama sphaerocarpa*; LO, *Lavandula officinalis*; GU, *Genista umbellata*; OE, *Olea europaea*; PP, *Phlomis purpurea*; SO, *Satureja obovata*; AC, *Anthyllis cytisoides*; RO, *Rosmarinus officinalis;* PA, *Persea americana*; MI, *Mangifera indica*; Ach; *Annona cherimola*; EJ, *Eriobotrya japonica*; TM, *Thymus mastichina*; LD, *Lavandula dentata*.

where W_t is the amount of material at time t, W_o is the amount of material at time 0. From this equation, we calculated the decomposition constant k (yr^{-1}) (Olson, 1963):

$$k = - \ln (W_t / W_o) \qquad \text{(Eq. 2)}$$

The mean residence time (R_t) of leaf litter in each plant cover was estimated by the inverse of k (Waring and Schlesinger, 1985):

$$R_t = 1 / k \qquad \text{(Eq. 3)}$$

Carbon and nitrogen in the fresh initial leaves and in the remaining mass of the litter bags were determined by a elemental analyser (FISONS CARLO ERBA EA 1108 CHNS O). Soil analyses were made according to standard methods (MAPA, 1994).

Remaining biomass (leaf-litter mass loss at T_i), residence times, litter N and C content, litter C:N ratios were assessed by an analysis of variance (ANOVA) with time and species as the main effects, using SPSS 15.0 for Windows. The percentage of remaining nutrients (% C and % N) in the debris was calculated as the ratio between the leaf-nutrient content at T_i and its initial content (at T_0). Also, correlations among C:N and N, and mass losses were made.

3. Results and discussion

3.1. Weight loss and litter-decomposition rates in altered-ecosystem slopes (AES)

3.1.1. Subtropical crop leaf decomposition: mango, cherimoya, loquat and avocado

Mass-loss dynamics over the study period were best described by the single exponential decay model (Figure 2a). According to the decomposition rate (*k*), cherimoya reached the highest value (1.30 year^{-1}) and mango the lowest (0.64 year^{-1}). In fact, at 159 days (the first collection in the subtropical crop-litter experiment), the remaining biomass in mango, loquat, avocado, and cherimoya were 64.7, 60.6, 54.5, and 37.6%, respectively. Pooling of these data indicated that half of the debris was lost in less than 6 months (time = 159 days) for avocado and cherimoya. Mubarak et al. (2008) have reported that about 60% of the litter in mango remained at the end of their experiment (3 months), and 50% weight was lost after 4.4 months. Thus, half of the debris was found later in the present experiment, since at 159 days (approximately 5.3 months), the remaining biomass for mango was still 64.7%. The aforementioned researchers found *k*-decomposition rates for mango of 2.08 years^{-1}, 3.3-fold higher than our k. This may be a consequence of the decay model itself, since biomass decrease is faster at the beginning and becomes slower at the end –that is, our experiment lasted 536 days and Mubarak et al. (2008) only 84 days. On the other hand, Musovoto et al. (2000) found that 18 months after placing the litter in the soil, 45% of the mango litter still remained undecomposed. Vasconcelos et al. (2007) reported slightly lower *k* values for *Annona paludosa* (1.13 years^{-1}) in an experiment in forest regrowth in the Brazilian Amazon. However, we found no studies on litter decomposition for cherimoya, loquat, or avocado. Differences in litter-decomposition rates are strongly related to weather conditions, and therefore the variations in *k* values could be related to the climatic characteristics of an area.

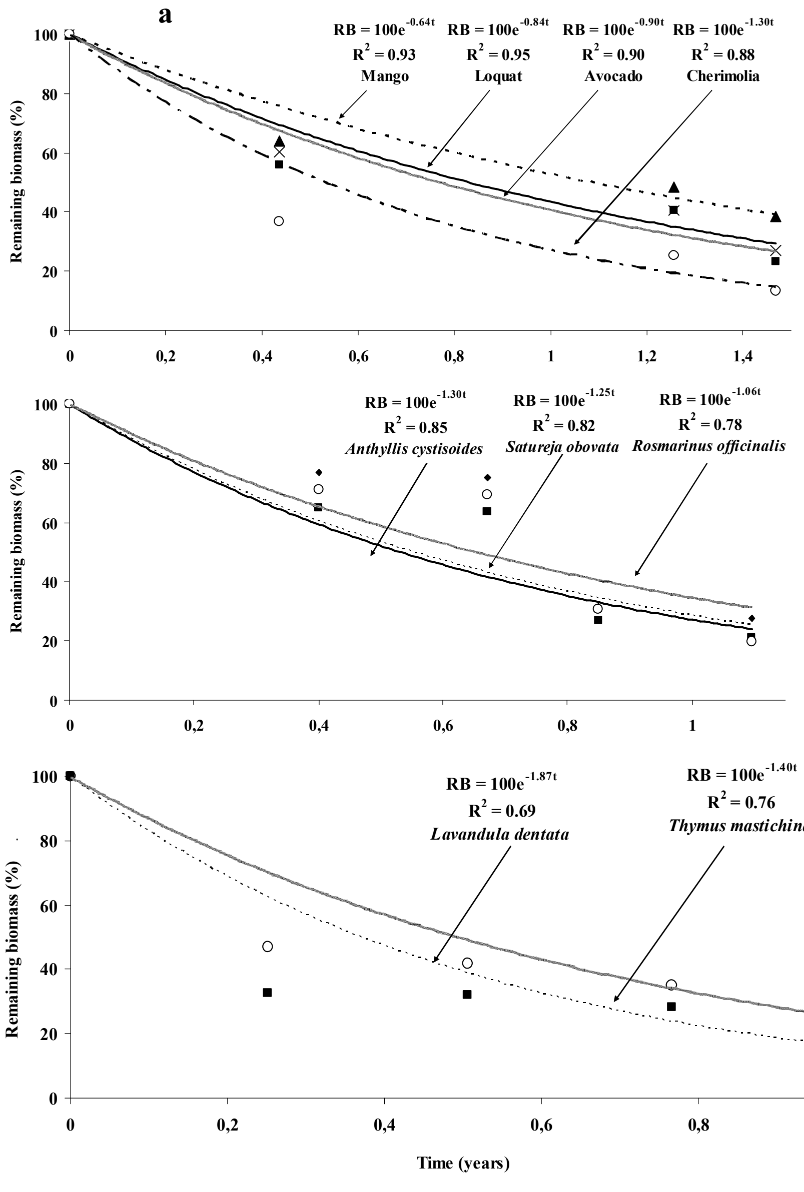

Figure 2. Percentage of remaining biomass (dry weight) in the leaf litter studied in the AES during the decomposition process. Negative exponential equations are used to express the percentage of biomass remaining with time (Eq. 1). Each point is the average of the biomass percentage remaining in the different samples taken at the same retrieval at T_i **(a).**

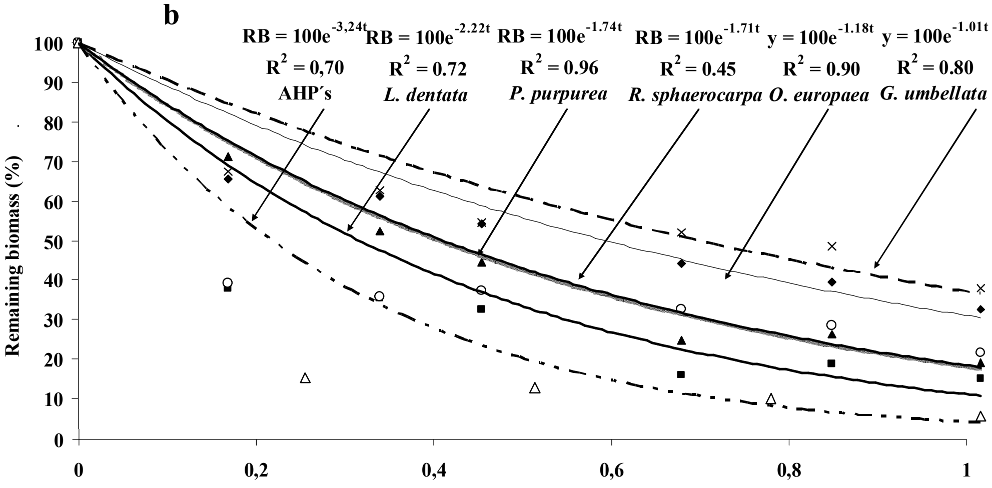

Figure 2. (Cont.). Percentage of remaining biomass (dry weight) in the leaf litters studied in the UES during the decomposition process **(b)**. AHPs, annual herbaceous plants mixture.

Thus, residence time (R_t) at the end of the subtropical leaf-decomposition experiment, for cherimoya, loquat, avocado, and mango, were 0.77, 1.05, 1.11 and 1.56 years, respectively (Table 2). The mean residence time for mango was 2.03-fold higher than for cherimoya. In this sense, the remaining biomass at T_f (the last retrieval, t = 526 days) was regressed against the initial C:N ratio (Figure 3), and we found a strong relationship between the two variables. Mango had the highest C:N ratio at the beginning of the experiment and it had the most persistent leaves, whereas the opposite trend was found for cherimoya. The remaining biomass (RB) values for cherimoya, loquat, avocado, and mango were 13.4, 26.9, 23.2, and 38.7%, respectively, and the ANOVA results for the remaining biomass at T_f in subtropical leaves litter showed significant differences among the four crops ($p < 0.01$) (Table 2). Furthermore, we found significant differences over time among the plants studied ($p < 0.01$); in this sense, decomposition patterns in loquat and cherimoya were similar, with significant differences in the remaining biomass among the three retrieval periods, indicating high and constant decomposition of the litter for these two crops. On the contrary, avocado and mango showed significant differences only between the first and second retrieval, indicating a slowdown of the decomposition process over time.

Table 2. Summary of litter-mass dynamics for the plants studied in the two sloped ecosystems.

Plant	k (year^{-1})	Residence time (R_t, years)	Remaining biomass at T_f (%)
Altered Ecosystem Slopes (AES)			
Subtropical crops			
Annona cherimola	1.30	0.77	13.4 a ± 5.1
Eriobotrya japonica	0.95	1.05	26.9 ab ± 8.0
Persea americana	0.90	1.11	23.2 ab ± 11.5
Mangifera indica	0.64	1.56	38.5 b ± 8.2
AMMPs			
Thymus mastichina	1.40	0.71	29.0 a ± 7.8
Anthyllis cytisoides	1.30	0.77	21.5 ab ± 1.6
Satureja obovata	1.25	0.80	19.7 ab ± 1.3
Rosmarinus officinalis	1.06	0.94	27.7 a ± 4.3
Lavandula dentata	1.87	0.53	17.7 b ± 2.6
Unaltered Ecosystem Slopes (UES)			
AHPs	3.23	0.31	5.5 a ± 0.7
Lavandula officinalis	2.22	0.45	14.9 ab ± 5.5
Phlomis purpurea	1.74	0.57	19.2 abc ± 8.8
Retama sphaerocarpa	1.71	0.58	21.7 bc ± 2.9
Olea europaea cv sylvestris	1.18	0.85	32.6 cd ± 4.6
Genista umbellata	1.01	0.99	37.9 d ± 6.6

AHPs annual herbaceous plants; Average ± standard deviation. Different letters within each group of plants mean significant differences among them (Tukey test, $p < 0.05$). Decomposition rate (k), residence time (R_t), and biomass remaining at the end of the experiment (T_f)

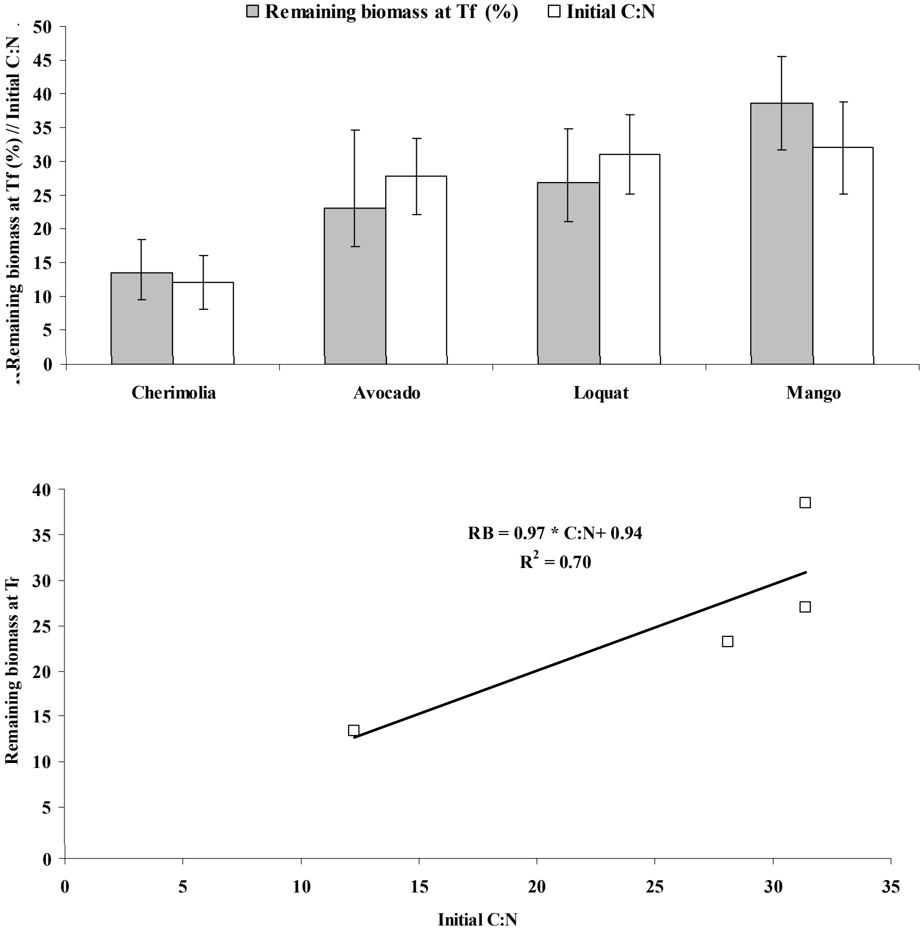

Figure 3. Relationship between the initial C:N ratio and remaining biomass (RB) at T_f (536 days) for the subtropical crops studied. Vertical bars mean standard deviation (n = 8) **(a).** Lineal regression between initial C:N ratio and remaining biomass at T_f **(b).**

Average daily decomposition rates of leaf litter in the four studied subtropical crops are shown in Figure 4. Average daily biomass-loss rates for cherimoya ranged from 3.97 mg g^{-1} day^{-1} during the first period (0-159 days) to 1.61 mg g^{-1} day^{-1} for the second period (459-536 days). However, for mango these rates were 2.26 mg g^{-1} day^{-1} and 1.14 mg g^{-1} day^{-1}, for the first and second period, respectively, signifying that cherimoya had average daily decomposition rates of 1.8- and 1.4-fold higher than mango for the first and second period, respectively. This difference could be due to the type of leaves of the two trees, given that mango has coriaceous leaves and contributes less to the litterfall process, since it is an evergreen tree; on the other hand, cherimoya has smooth and more biodegradable leaves and it is a semideciduous plant.

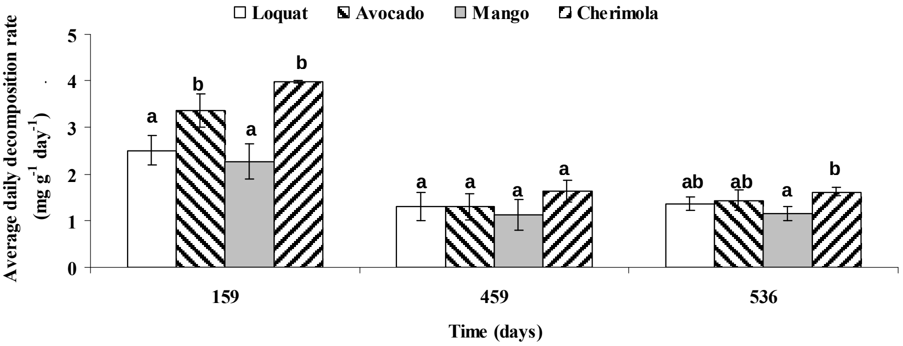

Figure 4. Average daily decomposition rate of subtropical leaves during the study period. Bars show standard deviation (n = 8). Different letters with the same day-group mean significant differences among plants (Tukey test, $p < 0.05$).

This implies that litter from cherimoya contributed earlier to the nutrient recycling compared to the rest, since most of the initial biomass was completely lost at the end of the experiment. It should be emphasized, however, that the effect of plant species on nutrient cycling is determined by both the mass-loss rate from the litter and by the total amount of litter produced per unit ground area (Chapin, 1991).

3.1.2. Aromatic, medicinal, and melliferous plant (AMMPs) decomposition

Decomposition constants (k) for *Thymus mastichina*, *Rosmarinus officinalis*, *Anthyllis cytisoides*, *Satureja obovata*, and *Lavandula dentata* were 1.40, 1.06, 1.30, 1.25, and 1.87 years^{-1}, respectively (Figure 2a, Table 2). At the end of the study the remaining biomass values were 29.0, 27.7, 21.5, 19.7, and 17.7% for *T. mastichina, R. officinalis, A. cytisoides, S. obovata* and *L. dentata*, respectively. Comparing the AMMPs studied, the percentage of biomass remaining for *L. dentata* and *S. obovata* were 39 and 32% lower than for *Thymus*, which reached the highest remaining biomass percentage. *Rosmarinus* and *Thymus* were the most persistent. The regression between the remaining biomass at T_f (RB_f) and the initial C:N ratio or N, (with the exception of *Thymus*) gave the following results: there was a strong direct lineal relation between RB_f and initial C:N ($RB_f = 0.30 * C:N + 12.3$, $R^2 = 0.96$, $p < 0.05$) (Figure 5a), and this relationship was inverse with the initial N content (%) and RB_f ($RB_f = -7.28 * N + 33.0$, $R^2 = 0.86$) (Figure 5b).

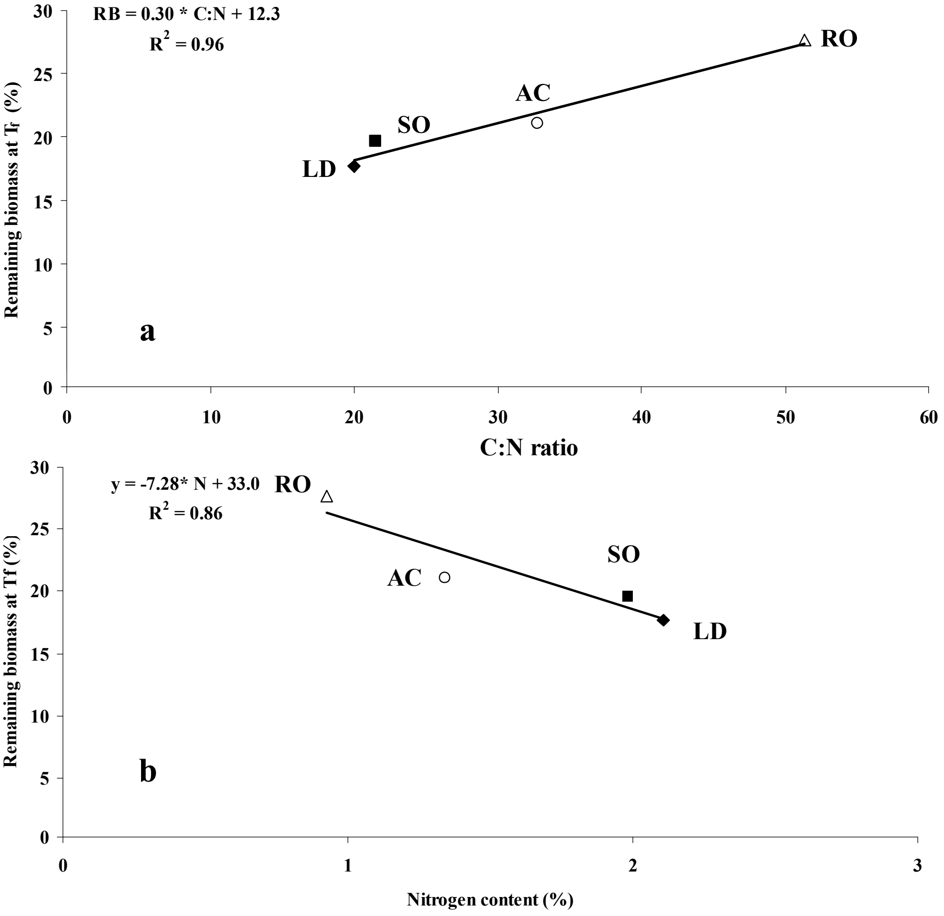

Figure 5. Linear relationship between remaining biomass (RB) at the end of the experiment (Tf) and initial C:N ratio in the litter **(a).** Linear relationship between remaining biomass at the end of the experiment (T_f) and initial N content in litter. LD, *Lavandula dentata*; AC, *Anthyllis cytisoides*; SO, *Satureja obovata*; RO, *Rosmarinus officinalis* **(b).**

These relationships were not statistically significant when *Thymus mastichina* was included in the regression, because this plant decomposed slowest and had a lower C:N and a higher N content than expected. Decay decomposition for *Thymus* was presumably more dependent on other quality parameters, such as lignin-N ratio, lignin concentration or soluble polyphenols (Berg and Staff, 1981; Palm and Sánchez, 1991; Mtambanengwe and Kirchmann, 1995).

3.2. Weight loss and litter-decomposition rates in unaltered-ecosystem slopes (UES): Native spontaneous woody shrubs and mixture of herbaceous plants (AHPs)

Regarding to *Lavandula officinalis*, *Phlomis purpurea, Retama sphaerocarpa*, *Olea europaea*, and *Genista umbellata*), we found decomposition rates of 2.22, 1.74, 1.71, 1.18, and 1.01 years^{-1}, respectively (Table 2, Figure 2b). For the random samples of mixed annual herbaceous plants (AHPs), we calculated a decay rate of 3.23 years^{-1}. Therefore, as expected, these types of plants reached the highest decomposition rates, 2.7- and 3.2-fold with respect to the most persistent shrubs (*G. umbellata* and *O. europaea*). This type of herbaceous vegetation also proved to be very effective in the runoff and erosion control, since it was used as a cover treatment in an erosion plot in other studies in the same area (Rodríguez et al., 2006; Rodríguez et al., 2009). After one year, AHPs, *L. officinalis* and *P. purpurea* had lost 94, 85 and 80% of their original dry weight, whereas *G. umbellata* and *O. europaea* had lost only 37.9 and 32.6%, respectively. The Tukey test showed the following relationship in relation to the average remaining biomass at T_f: AHPs < *L. officinalis* < *P. purpurea* < *R. sphaerocarpa* < *O. europaea* < *G. umbellata* (Table 2) for the overall study period ($p < 0.05$). A rapid initial phase of mass loss, which can be attributed to the readily soluble components of the litter was observed in the five shrubby species, but it was more pronounced in *L. officinalis* and *R. sphaerocarpa*, in which more than 50% of the mass had been lost during the first two months. The initial C:N ratio for the five shrubs studied and AHPs was a good predictor of the remaining biomass at the end of the study period ($R^2 = 0.93$, $p < 0.01$; Figure 6a). In this sense, *Genista* and *Olea* were the plants with the highest C:N ratio and they were the most persistent, whereas AHPs, *Lavandula,* and *Phlomis* had the lowest C:N and were the most easily degraded (Figure 6b). Our study for the five spontaneous shrubs and AHPs, showed a good fit for the relationship between C:N ratio and percentage of remaining biomass. These results agree with the findings of other authors for different species

(Edmonds, 1980; Moro and Domingo, 2000). Therefore, the mixture of herbaceous annual and biannual plants reached the highest decomposition rates.

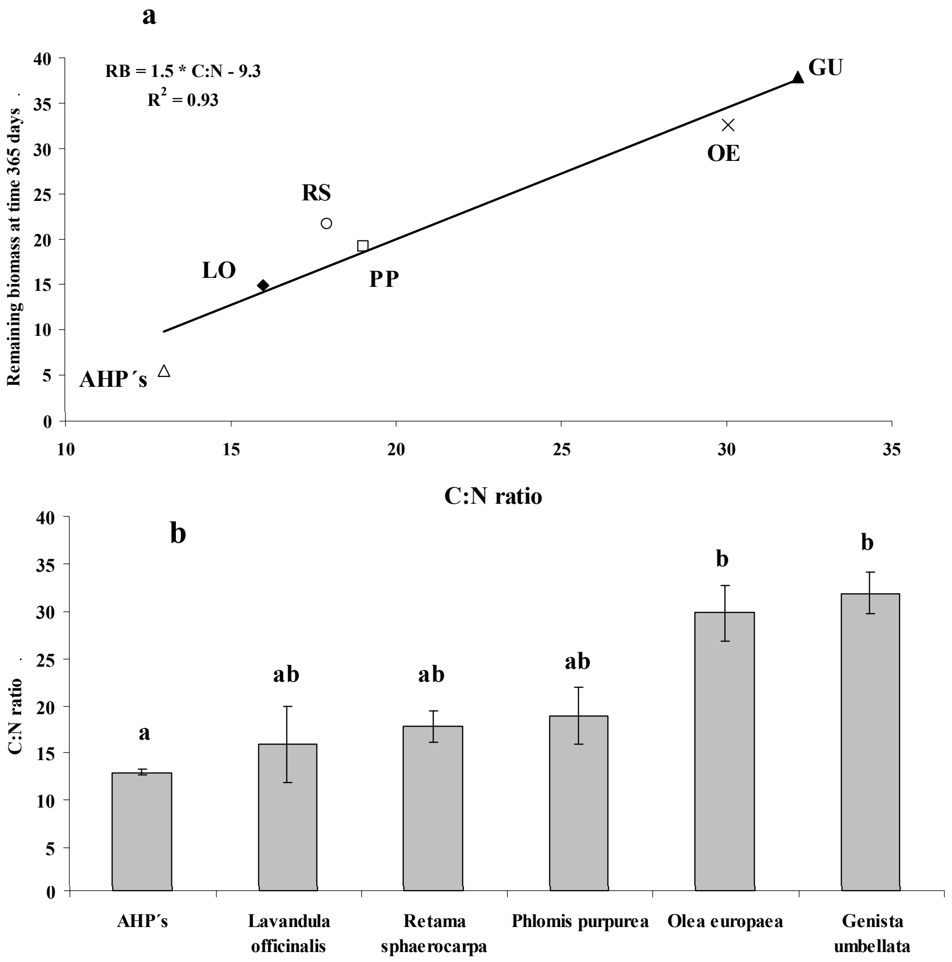

Fig. 6. Relationship between the initial C:N ratio and remaining biomass at Tf (365 days) for the plants studied in the unaltered-ecosystem slope. AHPs, annual herbaceous plants; LO, *Lavandula officinalis*; PP, *Phlomis purpurea*; RS, *Retama sphaerocarpa*; OE, *Olea europaea*; GU, *Genista umbellata* **(a)**. C:N ratios at the beginning of the experiment **(b)**; Different letters are statistically different at level $p < 0.05$ by Tukey analysis. Vertical bars mean standard deviation. (n = 6).

This is due to the types of plants (more easily degraded) and also to the mixture itself, since it is well known that non-additive litter-mixing effects prevail; that is, litter-mass loss in mixtures is greater than in pure litters (Gartner and Cardon, 2004), suggesting that some interactions among different litter species affect litter decomposition (Hättenschwiler et al., 2005).

3.3. Nitrogen and carbon dynamics over time in AES

3.3.1. Subtropical crops nitrogen dynamics: mango, cherimoya, loquat, and avocado

The tropical and subtropical species studied showed a wide range of variations in N concentrations. For the overall study period, the N concentration in litter reached the highest in cherimoya and the lowest in mango (average of 3.23 and 1.71%, respectively, $p < 0.05$). However, mango N concentrations did not significantly differ from avocado and loquat (2.20 and 1.78%, respectively). For the four species, there was a significant negative relation between the percentage of remaining biomass at the end of the experiment (RB_f) and the initial N concentration ($RB_f = 42.2 - 11.5 * N$; $p < 0.05$). The inverse linear relationship between percentage of remaining biomass and nutrient concentration such as nitrogen in the litter is very common for many other types of plants, as demonstrated by several authors (Aber and Melillo, 1980; Blair, 1988; Gallardo and Merino, 1992). The changes in mass indicate respiration loss of organic carbon, while changes in nitrogen content indicate changes in the quantity of microbial protoplasm (Aber and Melillo, 1980). Figure 7a shows the evolution of the N content (%) over time for the four crop species. Also, to study net N dynamics, we expressed the N content of the litter as the initial percentage (Figure 7b). Dynamics in N content are usually characterized by a net immobilization (net increase in content due to incorporation of N into the litter from the surroundings) and net mobilization (release). The immobilization of N during decomposition often occurs in other temperate ecosystems (Hasegawa and Takeda, 1996; Enoki and Kawacuchi, 2000). In our study, the maximum amount of N immobilized was affected by the plant species. In mango and loquat, the species with the highest initial C:N ratios (32.0 and 31.0, respectively), also registered the highest amount of N immobilized (Figure 7). On the contrary, cherimoya and avocado had the lowest initial C:N ratio (12.1 and 27.7, respectively) and the highest N release (Figure 7a,b). Nitrogen net release in cherimoya and avocado occurred in the first 162 days of the study and was very pronounced, suggesting that its concentration in the leaf litter exceeded the needs of decomposers (Swift et al., 1979; Vogt et al., 1986). During the first four months, a net immobilization of approximately 21% and 73% occurred for mango and loquat respectively, whereas a net mobilization took place for cherimoya and avocado (12 and 7%, respectively).

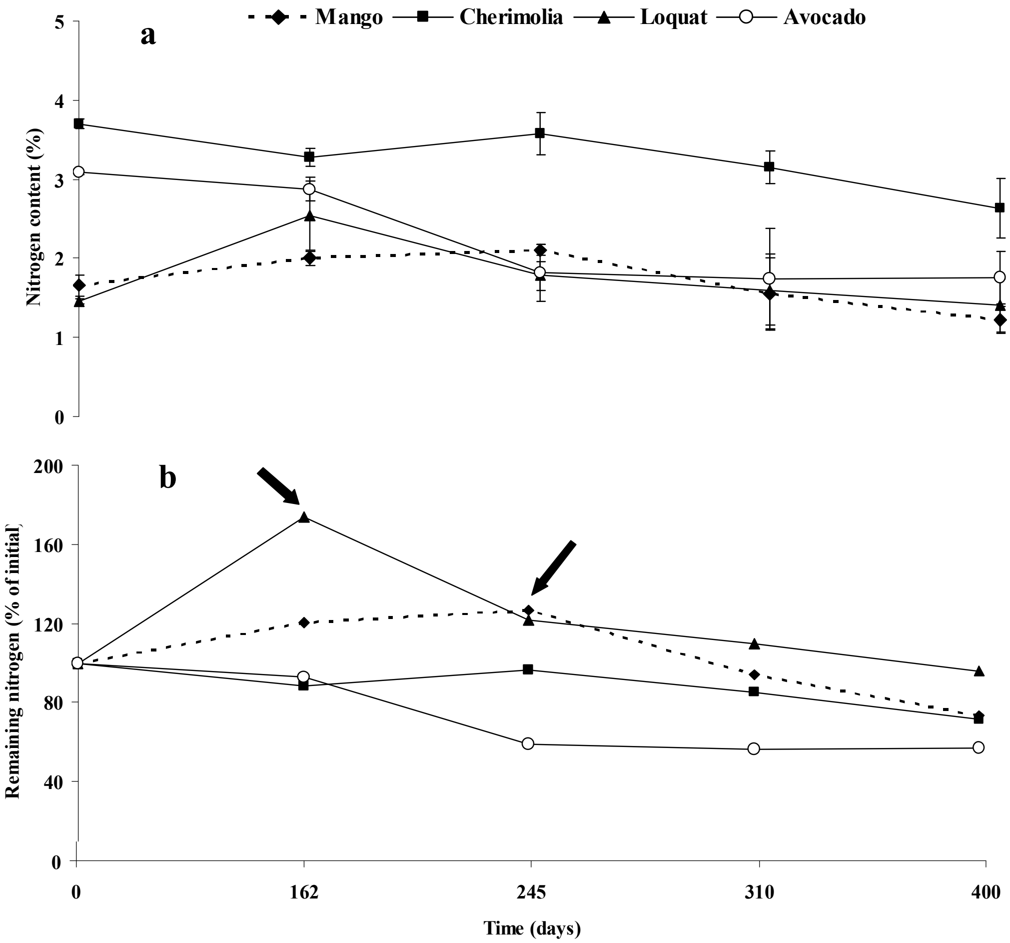

Fig. 7. Changes in N content. Vertical bars represent standard deviations (n = 8) **(a).** Remaining N (% of initial) during the decomposition period. Arrows indicate the retaining period in *Eriobotrya japonica* and *Mangifera indica* **(b).**

The percentage of remaining N at the end of the study was for cherimoya and avocado 71.2 and 56.8 %, respectively. In this sense, under tropical conditions, Musovoto et al. (2000) reported immobilization (1.95-fold of initial N content) during decomposition of mango litter. The increases in N concentration in litter were due to mechanisms such as microbial immobilization of N (Koeing and Cochran, 1994), fungal translocation, throughfall, and insect frass (Melillo et al., 1992).

Changes in carbon content were statistically significant among each retrieval ($p < 0.05$) for the four species, except for cherimoya. There was a general decreasing trend for the C content in the litter of four plants, more marked in avocado and mango, which had only 60 and 67% of the remaining C at the end of the experiment (Figure 8).

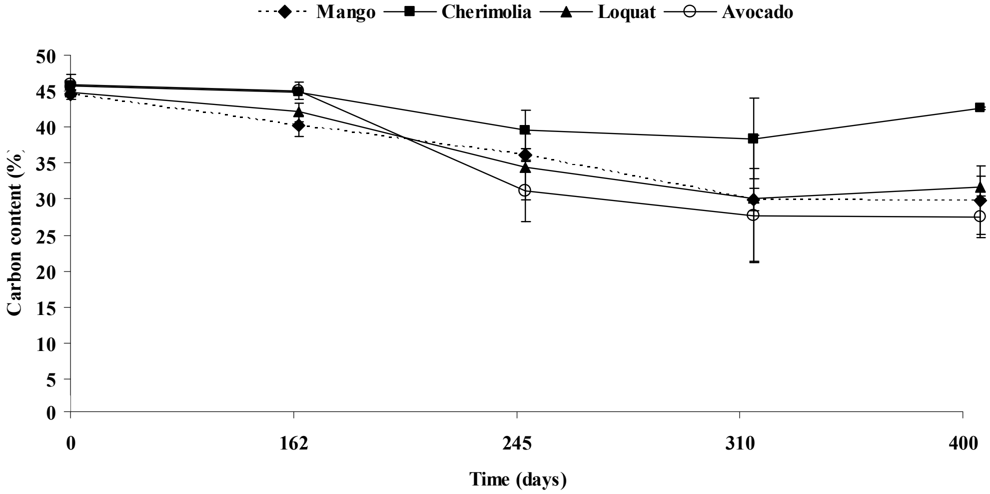

Fig. 8. Carbon-content evolution over time for the subtropical crops. Vertical bars represent standard deviation (n = 8).

Therefore, the results of this study show that farmers would benefit from using litter from subtropical crops to enhance long-term soil organic matter and nitrogen accumulation. Loquat and mango showed the highest accumulation of N, and thus they could be used for long-term soil fertilization. On the other hand, cherimoya accumulated higher amounts of C than the rest of the subtropical leaves studied.

3.3.2. Aromatic, medicinal, and melliferous plants (AMMPs)

The AMMPs studied showed different patterns with regard to N concentrations. The mean concentration of N in the leaves at the end of the study period for the plants relative to the initial concentration decreased in *Lavandula dentata*, *Thymus mastichina*, and *Satureja obovat*a. Moreover, a net mineralization occurred from the beginning of the experiment for *Thymus mastichina,* and *Lavandula dentata.* However, N concentration increased in *Rosmarinus officinalis* and *Anthyllis cytisoides* (Figure 9). For *S. obovata*, *A. cytisoides,* and *R. officinalis*, an initial peak increase (at 162 days retrieval) was detected, with a maximum concentration of 151, 157, and 174%, respectively, with respect to initial N content. Other authors have reported peaks in N-concentration followed by net release in Mediterranean environments. In this sense, Santa Regina *et al.* (1997) found an increase in N-concentration during the decomposition of *Quercus pyrenaica* and *Quercus lanuginosa* with a net release after 36 months of study.

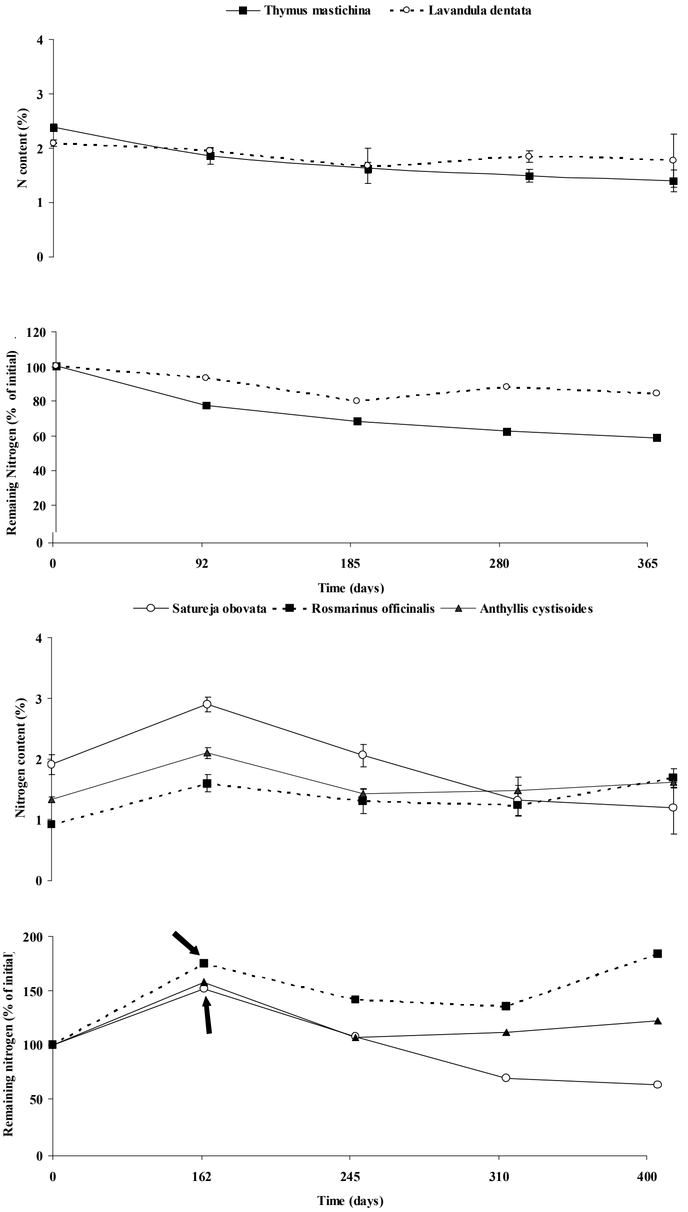

Fig. 9. Changes in N content **(a)** and remaining N (% of initial values) during the decomposition period in the five aromatic and medicinal plants **(b)**. Vertical bars represent standard deviations (n = 6 for *Thymus mastichina* and *Lavandula dentata*; n = 8 for *Satureja obovata*, *Anthyllis cytisoides* and *Rosmarinus officinalis*). Arrows indicate the retaining period in *Rosmarinus officinalis, Satureja obovata*, and *Anthyllis cytisoides.*

Moro and Domingo (2000) found a N-immobilization in *Pinus pinaster, Pinus nigra, and Cistus laurifolius* over 140%, 24, and 25%, respectively, of their original content. Other studies have noted increases in N contents in litter (Bocock, 1963; Edmonds, 1979), particularly in the early stages of decomposition. When N is a limiting factor during litter decomposition, microbes and fungi not only immobilize N but may import N from the surrounding litter substrates (Bates *et al.,* 2007). The carbon content did not undergo significant changes (Figure 10).

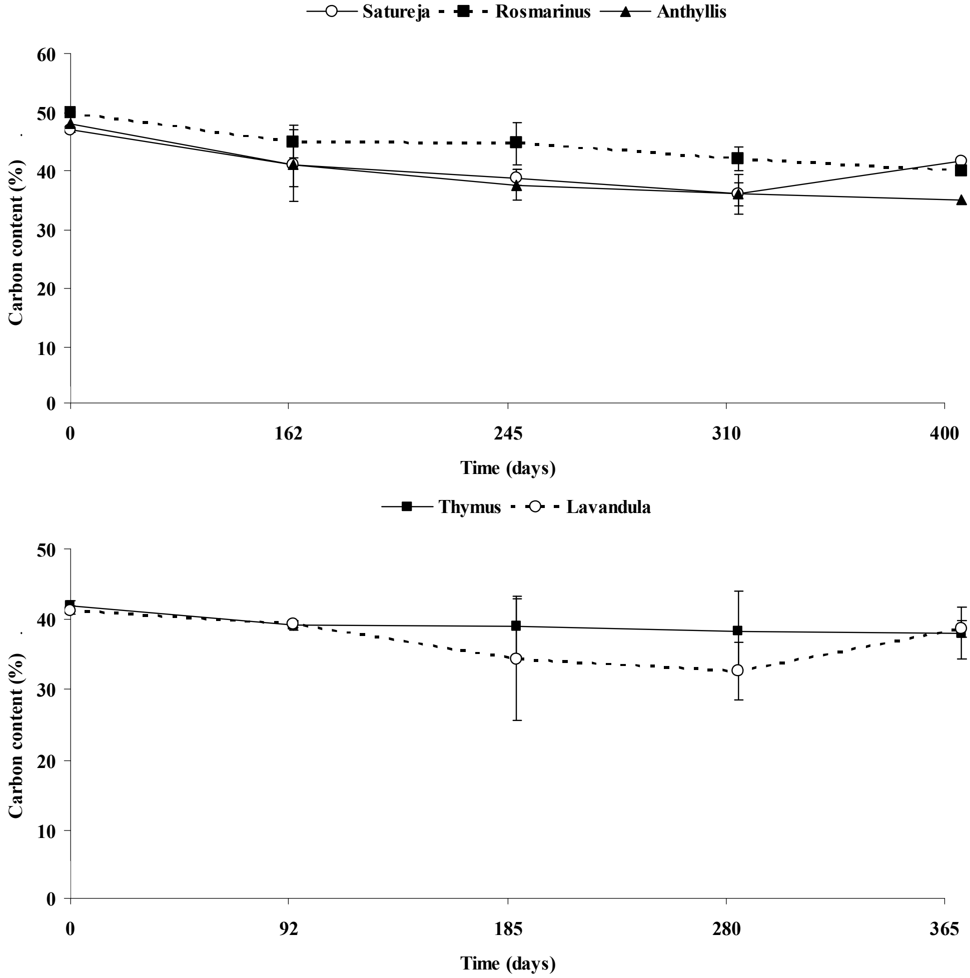

Fig. 10. Carbon content evolution in aromatic and medicinal plants. Vertical bars represent standard deviations. (n = 6 for *Thymus mastichina* and *Lavandula dentata*; n = 8 for *Satureja obovata*, *Anthyllis cytisoides* and *Rosmarinus officinalis*).

However, the C:N ratio showed different patterns in the plants studied, increasing from 17.5 to 27.7 in *Thymus* ($p < 0.05$), from 17.6 to 23.4 in *Lavandula*, and from 21.2 to 26.4 in *Satureja* (although in the latter two plants these increases were not significant). On the contrary, the C:N ratio declined in *Rosmarinus* from 50.6 to 27.9 and in *Anthyllis* from 32.4 to 24.3 (both significant $p < 0.05$). This decline in the C:N ratio could be due to the immobilization of N. Thus the cultivation of *T. mastichina*, *L. dentata* or *S. obovata* on the taluses and terraces of subtropical crops in Mediterranean conditions could be an extra N input to the soil for a short-term period due to the fast N-release rates. On the contrary, *Rosmarinus* and *Anthyllis* litter could be used to improve the long-term N content in soil.

1.4. *Nitrogen and carbon dynamics over time in UES: Native spontaneous shrubs and AHPs*

The nitrogen content in the litter varied over time in the five shrubby species (Figure 11a). In *Retama* and *Olea*, the N content increased for the overall study period (final N values in *Retama* and *Olea* were 120 and 146%, respectively; Figure 11b).

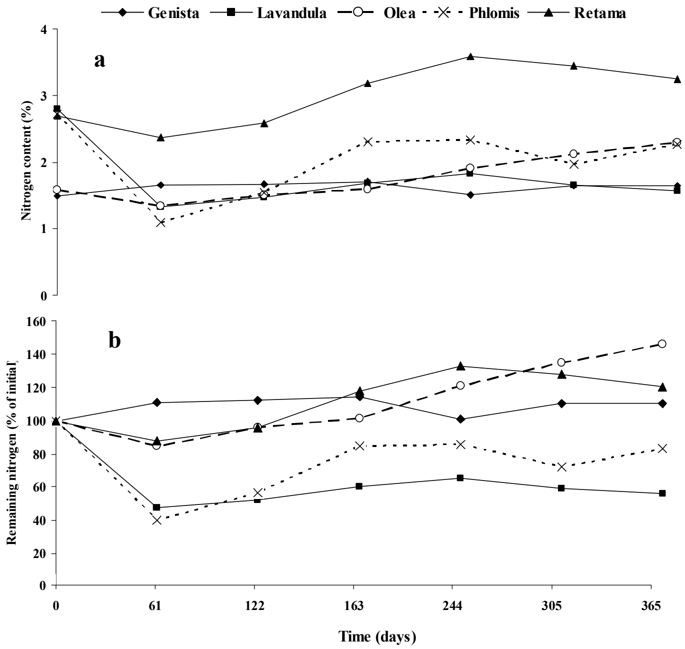

Figure 11. Changes in N content **(a)** and remaining N (% of initial) during the decomposition period in the five spontaneous shrubs **(b)**

On the contrary, *Lavandula* and *Phlomis* litter, decreased their N contents to 56 and 83% of the initial values, respectively (Figure 11b). The net N release began for *Lavandula* and *Phlomis* from the beginning of the experiment, with only 48 and 41% of the initial N-content, respectively, remaining after two months. By contrast, for AHPs, 90% of the N remained after three months. We found no net release in the rest of plants, but rather the opposite –net immobilization. However, Oliver *et al.* (2002) recorded 2.4% of the N content in *Retama* as not immobilized nor released, as the concentration after one year of experiment remained approximately the same. *Retama* and *Genista* are common legumes in semiarid environments of SE Spain, and both N-fixing plants showed a N-immobilization pattern. The mineralization of plant remains in N-fixing plants is an essential pathway of N transfer (Uselman et al., 1999). The carbon content in the remaining litter did not significantly change over time for the five shrubs, since the C content was 90.3, 93.0, 95.1, 90.0, and 105.2 % of the initial values for *Lavandula, Phlomis, Retama, Olea*, and *Genista*, respectively (Table 3).

Table 3. Average remaining biomass, C content, N content and C:N (% of the initial)

Spontaneous shrub	Remaining biomass (%)	C (%)	N (%)	C:N
Lavandula officinalis	14.9	90.3	56.2	166.2
Phlomis purpurea	19.2	93.9	83.3	116.0
Retama sphaerocarpa	21.7	95.1	120.4	80.6
Olea. europaea	32.6	90.1	146.0	73.8
Genista umbellata	37.9	105.2	110.4	95.5

A highly significant relationship between initial C:N ratio in leaves and remaining biomass at T_f was found for the five plants (RB at Tf = -6.4 + 1.3 * C:N; r = 0.87, $p < 0.01$). Therefore, we conclude that *Lavandula* and *Phlomis* had a high net N-release, whereas *Olea*, *Genista*, and *Retama* (these two later shrub legumes) had higher nitrogen immobilization. Thus, *Retama* and *Genista* litter are suitable for increasing N contents in soil over the longer term.

Consequently, when the two studied ecosystems, AES and UES, are compared, the k-decomposition rates for the plants in the AES varied from 0.64 to 1.30 years^{-1} for subtropical crops and 1.06 to 1.87 years^{-1} for AMMPs used on the taluses. On the other hand, *k*-decomposition rates ranged for UES from 1.01 to 3.23 years^{-1}. Therefore, in this type of scenario (UES), plants had higher decomposition rates, except for *Olea europaea* and *Genista umbellata*. In general, leaves in subtropical crops had low decomposition rates (except for cherimoya), but this situation was compensated for by the cultivation of AMMPs on the taluses, which in general had higher *k* constants. In UES, almost all the plants studied showed a net N immobilization, especially in the spontaneous woody shrubs. On the contrary, subtropical crops in the AES showed a net mobilization pattern, representing a rapid N source that could be available for tree uptake.

3.5. Net comparison in N-dynamics for the two studied agroecosystems

After studying the dynamics of N in both agroecosystems, we can compare net immobilization (net concentration increase) and mobilization (net concentration decrease). Table 4 shows the algebraic summing up of the N release of each species. The last column of Table 4 shows the average for the plants studied in each system so that we can compare the agro-ecosystems between as a whole. Negative values indicate that the concentration in the plant material remaining in the litter bags increased compared with the initial values, for a net N immobilization at each time step. Positive values mean the opposite, i.e. that N concentration in the plant decreased compared to the initial values, with net mobilization (N-release). As shown in the table, AES (subtropical crops and AMMPs) presented an average N-dynamic value of 1.15 and 0.20, respectively. An average value for these latter two would be 0.675. However, the N-dynamic value for the UES was 2.4-fold higher than the value for AES. Therefore, when agricultural crops (AES) replace native vegetation, the natural nutrient cycle is altered, with the mobilization (release) and cycling being slower. Thus, the alteration of the N cycle in the cultivation of subtropical could be compensated for by the planting of fast N-recycling plant covers such as *Thymus mastichina* (3.18), *Lavandula dentata* (1.12), *Lavandula officinalis* (7.26), or *Phlomis purpurea* (4.83).

Table 4. Algebraic summing up of the N release of each species and for the two agroecosystems studied

Stage	Mango	Cherimoya	Loquat	Avocado	Average AES-subtropical	*Satureja obovata*	*Rosmarinus officinalis*	*Anthyllis cytisoides*	*Thymus mastichina*	*Lavandula dentata*	Average AES-AMMPs
0	0	0	0	0		0	0	0	0	0	
1	-0.34	0.42	-1.08	0.22		-0.99	-0.68	-0.77	0.53	0.13	
2	-0.45	0.13	-0.32	1.27		-0.15	-0.38	-0.09	0.76	0.42	
3	0.10	0.55	-0.15	1.36		0.60	-0.32	-0.16	0.90	0.24	
4	0.44	1.07	0.06	1.34		0.71	-0.77	-0.30	0.99	0.33	
Summation	-0.25	2.17	-1.49	4.17	1.15	0.17	-2.16	-1.31	3.18	1.12	0.20

Table 4 (Cont.)

Stage	*Genista umbellata*	*Lavandula officinalis*	*Olea europaea*	*Phlomis purpurea*	*Retama sphaerocarpa*	Spont veget	Average UES
0	0	0	0	0	0	0	
1	-0.16	1.47	0.24	1.63	0.33	0.32	
2	-0.18	1.34	0.07	1.18	0.12		
3	-0.22	1.12	-0.02	0.42	-0.48	0.41	
4	-0.01	0.97	-0.33	0.39	-0.89	0.72	
5	-0.15	1.14	-0.55	0.76	-0.75		
6	-0.16	1.23	-0.73	0.46	-0.55	0.76	
Summation	-0.89	7.26	-1.32	4.83	-2.23	2.21	1.64

4. Conclusion

This work demonstrates the importance of litter decomposition and nutrient dynamics in this particular agroecosystem of south-eastern Spain. Among the four subtropical crops studied, cherimoya and loquat leaves decomposed fastest, and mango and avocado slowest. Leaves of cherimoya could contribute to a faster nitrogen-recycling whereas mango and loquat can be used for long-term build-up of soil N, but their residues would not be useful for short-term soil-N corrections. The use of fallen leaves for N cycling in subtropical orchards deserves particular attention and further studies to clarify the role of these leaves in improving and increasing the soil organic matter and N recycling in these marginal cultivation areas.

Among the aromatic-medicinal plants studied, *Lavandula dentata* decomposed very quickly and released N from the beginning; on the contrary, *Rosmarinus officinalis*, *Satureja obovata* and *Anthyllis cytisoides* immobilized N during the first five months. Spontaneous plant species growing in the area surrounding crops (AHPs) could also improve soil by combining a high net release of N together with a high decomposition rate.

The importance of annual and perennial shrubs and herbs in Mediterranean areas to protect the soil from erosion and runoff has been widely confirmed. Also, these types of plants improve soil organic matter due to the relatively fast recycling of the biomass (high k constants). UES had plants with higher k-decomposition constants, as expected, because in AES the leaves from subtropical crops contribute slowly to recycling of biomass. In AES this was compensated for by the planting of AMMP covers in the taluses of the terraces, which also protected the soil from erosion and eventual destruction of these structures. In this context, subtropical fruit production can be reconciled with environmental concerns, as in the case of the cultivation of aromatic-medicinal plants on the taluses of subtropical orchard terraces, providing soil protection against erosion, promoting nutrient recycling, and helping minimize soil-nutrients losses.

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Capítulo IV

Assessing the pollution risk and water use in orchard terraces with mango (*Mangifera indica* L.) and cherimoya (*Annona cherimola* Mill) by using drainage lysimeters

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Assessing the pollution risk and water use in orchard terraces with mango (*Mangifera indica* L.) and cherimoya (*Annona cherimola* Mill) by using drainage lysimeters

Rodríguez Pleguezuelo, C.R.[a,*], Durán Zuazo, V.H.[a,b], Martín Peinado, F.J.[c], Franco Tarifa, D.[d]

[a] IFAPA Centro Camino de Purchil. Aptdo. 2027; 18080 Granada, Spain.
Phone: (+34) 958 895 255; (+34) 647 199 854. Fax: (+34) 958 895 202;
*corresponding author E-mail: *crocio.rodriguez@juntadeandalucia.es*
[b] IFAPA Centro Las Torres-Tomejil. Crtra Sevilla-Cazalla, km 12.2; 41200 Alcalá del Rio (Sevilla) Spain.
[c] Departamento de Edafología y Química Agrícola, Universidad de Granada, C/Severo Ochoa s/n, 18071-Granada, Spain
[d] Finca "El Zahorí". Patronato de Cultivos Subtropicales Plaza de la Constitución 1, Almuñécar (Granada), Spain

ABSTRACT

Agricultural nonpoint-source pollution is the leading cause of water-quality degeneration of rivers and groundwater. In this context, the coast of Granada province (SE Spain) is economically an important area for the subtropical fruit cultivation. This intensively irrigated agriculture often uses excessive fertilizers, resulting to water pollution. Therefore, a two-year experiment was conducted using drainage lysimeters to determine the potential risk of nutrient pollution in mango (*Mangifera indica* L. cv. Osteen) and cherimoya (*Annona cherimola* Mill. cv. Fino de Jete) orchards. These lysimeters were used to estimate the nutrient budgeting for each crop. NO_3-N, NH_4-N, PO_4-P and K losses according to lysimeters were, respectively, 55.1, 12.4, 3.7, and 0.6 for mango and 61.8, 17.8, 4.9, and 0.5 kg ha^{-1} yr^{-1}, for cherimoya. NO_3, concentrations in the leachates ranged from 1.8 to 44.3 mg L^{-1}, and from 23.0 to 51.0 mg L^{-1}, for mango and cherimoya, respectively, in some cases exceeding the limits for safe drinking water. PO_4 also exceeded the permitted concentrations related to eutrophication of water, ranging from 0.07 to 0.5 mg L^{-1} and from 0.12 to 0.68 mg L^{-1} from mango and cherimoya lysimeters, respectively. With respect to the nutrient balance, N, P, and K removed by cherimoya fruits was 76.4, 5.5, and 22.6 kg ha^{-1} yr^{-1}, and for mango fruits 30.2, 3.3 and 27.8 kg ha^{-1} yr^{-1}, respectively. Nutrient losses in the leachates were surprisingly low, considering total N, P, and K applied during the year, in mango lysimeters 3.8, 0.11, and

12.6%, and in cherimoya lysimeters 7.7, 0.23 and 16.0%, respectively, indicating a potential soil accumulation and eventual loss risk, especially during torrential rains. Crop coefficient (*Kc*) values of mango trees varied within ranges of 0.35-0.67, 0.55-0.89, and 0.39-0.80 at flowering, fruit set, and fruit growth, respectively. *Kc* values for cherimoya trees had ranges of 0.58-0.67, 0.61-0.68, and 0.43-0.62 at flowering, fruit set and fruit growth, respectively. In this study, the *Kc* values of mango and cherimoya were significantly correlated to julian days. Therefore, the estimated WUE in the mango and cherimoya orchards reached 21.2 and 14.0 kg ha^{-1} mm^{-1}, respectively. Thus, this study highlights the urgency to establish the optimal use of fertilizers and irrigation water with respect to crop requirements, to preserve surface-water and groundwater quality, thereby achieving more sustainable agriculture in orchard terraces.

Keywords: irrigation, drainage lysimeter, groundwater, terraces, mango, cherimoya.

2. Introduction

Diffuse nutrient loss from conventional agriculture is degrading surface- and groundwater quality throughout Europe, leaving water at risk of not meeting the targets set by the Water Framework Directive (WFD 2000/60 EC). Mitigation methods to diminish diffuse agricultural nutrient loss need to be implemented where water bodies have been identified as being at risk of not reaching good status by 2015. Though the effectiveness of individual mitigation methods has usually been assessed in controlled experiments, it is necessary to quantify the impact under a wider range of environmental and agricultural conditions. Therefore, it is imperative to compare the attributes and usefulness of different approaches (*e.g.* direct measurements, nutrient budgeting, risk assessment, and modelling) to assess the efficiency of actions to mitigate sources of transport of nitrogen (N), phosphorous (P) and potassium (K) from agricultural land to water. The N fertilizers are the main cause of nitrate (NO_3) leaching (Follet, 1989; Germon, 1989), and can degrade water quality (Ren et al., 2003). This danger becomes urgent, as their use is forecasted to double or almost triple by 2050 (Tilman et al., 2001).

According to Follet (1989), NO_3 leaching depends on several factors such as soil texture, plant uptake, fertilizer input, drainage, and some transformation N processes (immobilization, mineralization, nitrification) promoted by poor soil and crop management (Follet, 1989). Phosphorus, though essential for plant growth, is often applied in amounts that exceed the uptake capability of crops. Most of this excess is often bound to the soil and therefore the losses of soluble phosphate (PO_4^{3-}) in surface flow and runoff tend to be quite low (Balogh and Walker, 1992). The main processes for P losses from agricultural fields to surface waters are erosive surface runoff and subsurface transfer and this is especially risky when excessive loading of fertilizers is applied to sandy soils with limited PO_4^{3-} sorption (Peaslee and Philips, 1981). P together with N is often the limiting nutrient for primary production in lakes and streams. Consequently, a high P level increases primary production and oxygen demand, promoting eutrophication of the surface water (Sharpley and Smith, 1990). Since P concentrations as low as 10 μg L^{-1} can stimulate algal growth (Sharpley and Smith, 1989), inputs need to be controlled and the nature as well as the mechanisms of release into waters become essential to any management control strategy.

On the contrary, high K concentrations in runoff and subsurface water are thought to have less critical effects on groundwater quality and on the overall environment. However, there are important interactions of K with Ca and Mg that have an impact on crops, grazing animals, and human nutrition (Wilkinson et al., 2000). In fact, most regulations on drinking water do not establish a limit concentration for this element, although a maximum admissible concentration value for K in water for human consumption of 12 mg L^{-1} has been established by the European Community (EEC, 2000). This threshold value has been criticised because it has no toxicological or physiological justification and is unnecessarily low from nutritional and health standpoints (Grossklaus, 1992).

Many authors (Addiscott et al., 1991; Syvertsen and Sax, 1999; Kramer et al., 2006; Godlinski et al., 2008) have reported that one of the most direct approaches to investigate percolation of these nutrients (N, P, K) to groundwater is the use of lysimeters, which comprise a confined, intact soil column with a provision for solution sampling that allows an accurate measurement of nutrient source/sink relationships. Also, such studies offer the most direct approach to investigate percolation of these plant nutrients to groundwater, and they provide precise results, since lysimeter walls create precisely known barriers.

In this context, the coast of Granada (SE Spain) is an important growing area for subtropical crops such as mango (*Mangifera indica* L.), cherimoya (*Annona cherimolia* M.), avocado (*Persea Americana* M.), loquat (*Eriobotrya japonica* L.) and other fruits (Durán et al., 2003; 2006a). Concretely, during 2006 about 90.1% of the cultivated area of cherimoya in Andalusia was located in the province of Granada, with a total production of 25,001 t (86.6% of the production in Andalusia; Anuario Estadístico 2006). On the other hand, the cherimoya is a subtropical fruit tree of increasing interest for European markets (Lüdders, 2002; Durán et al., 2006a), with Spain in the leading country in terms of cultivated area and production, with approximately 3,600 ha, with yield of 35,000 t (Cautín and Agustí, 2005). In 2000, the EU registered a total of 6,647 t mangoes imported from Spain (from a total of 117,102 t imported globally; Cohen et al., 2001). Particularly, in Spain, mango cultivation is feasible primarily in the provinces of Granada and Málaga, with some 900 ha of mango orchards soon to exceed a yield of 6,000 t yr^{-1}.

These crops have been established on orchard terraces, which strongly alter the soil profile. This, together with the climatic characteristics of this area (scare but often of high-intensity rainfall), sometimes causes pollution from agricultural inputs (fertilizers, pesticides, herbicides, etc.) and soil erosion due to the presence of the taluses without vegetal protection, since leaving bare soil in the most common practice among local farmers (Durán et al., 2004; Rodríguez et al., 2009).

Finally, knowledge of evapotranspiration is essential for efficient water management, given that accurate predictions are needed in order to adjust irrigation volume and frequency to crop water demand. However, measurements of evapotranspiration and crop coefficients from mature mango and cherimoya trees are not abundant.

In the present study, drainage lysimeters are used to assess the effects of conventional agriculture of mango and cherimoya orchards growing in terraces: (i) to compare via lysimeters the quality and quantity of soil water effluent, (ii) to account for and evaluate components of N, P, and K transport and their environmental effects, establishing balancing budgets (soil-plant-water), and (iii) to determine water-use performance for mango and cherimoya by estimating the crop coefficients (K_c).

3. Materials and methods

2.1. Site description

The study was performed on orchard terraces of mango a cherimoya located some 7 km north of the Mediterranean coast near Almuñécar (Granada, SE Spain) on the experimental farm “El Zahorí”(36º48´00´´N, 3º38´0´´W) at an elevation of 180 m a.s.l.. The study terrace, representative of those commonly found in the study area, is a reverse-sloped bench-terrace type with a toe drain measuring 160-170 m long. The platform was 2-3 m wide and the talus 3-5 m high. Mango (*Mangifera indica* L. cv. Osteen) trees were planted on a single row of bearing trees, spaced 3 m apart (600 trees ha^{-1}). Cherimoya (*Annona cherimola* cv. Fino de Jete) trees were also planted on a single row spaced 7 m apart (280 trees ha^{-1}). The conventional fertiliser application rate of N, P, and K per tree was, respectively, 829, 241, and

276 gr for cherimoya, and 638, 274 and 221 gr for mango (Table 1). The soils of the zone are Typical Xerorthent (Soil Survey Staff, 1999), with 684 g kg^{-1} of sand, 235 g kg^{-1} of silt and 81 g kg^{-1} of clay, containing 9.4 g kg^{-1} of organic matter, and 0.7 g kg^{-1} of N, with 14.6 mg kg^{-1} P, and 178.7 mg kg^{-1} assimilable K (MAPA, 1994).

Table 1. Fertilizer timing, source, and rate for cherimoya and mango lysimeters

Date	Source	Rate	N	P	K
				(kg ha^{-1})	
		Cherimoya lysimeters			
1-Mar	12-61-0	28	3.4	17.1	0
15-Mar	12-61-0	28	3.4	17.1	0
1-Apr	12-61-0	28	3.4	17.1	0
15-Apr	12-61-0	28	3.4	17.1	0
1-May	33-0-0	70	23.1	0	0
15-May	33-0-0	70	23.1	0	0
1-Jun	33-0-0	70	23.1	0	0
15-Jun	33-0-0	70	23.1	0	0
1-Jul	33-0-0	61.6	23.1	0	0
1-Jul	13-0-46	33.6	4.36	0	15.5
15-Jul	33-0-0	61.6	20.3	0	0
15-Jul	13-0-46	33.6	4.4	0	15.5
1-Aug	33-0-0	61.6	20.3	0	0
1-Aug	13-0-46	39.2	4.4	0	15.5
15-Aug	33-0-0	61.6	20.3	0	0
15-Aug	13-0-46	39.2	4.4	0	15.5
1-Sep	33-0-0	61.6	20.3	0	0
1-Sep	13-0-46	39.2	4.4	0	15.5
		Mango lysimeters			
3-Mar	12-61-0	31.5	3.8	19.2	0
10-Mar	12-61-0	31.5	3.8	19.2	0
17-Mar	12-61-0	31.5	3.8	19.2	0
24-Mar	12-61-0	31.5	3.8	19.2	0
31-Mar	12-61-0	31.5	3.8	19.2	0
7-Apr	12-61-0	31.5	3.8	19.2	0
14-Apr	12-61-0	31.5	3.8	19.2	0
21-Apr	12-61-0	31.5	3.8	19.2	0

28-Apr	12-61-0	31.5	3.8	19.2	0
12-May	33-0-0	63	20.8	0	0
19-May	33-0-0	63	20.8	0	0
26-May	33-0-0	63	20.8	0	0
2-Jun	33-0-0	63	20.8	0	0
9-Jun	33-0-0	63	20.8	0	0
16-Jun	33-0-0	63	20.8	0	0
23-Jun	33-0-0	63	20.8	0	0
30-Jun	33-0-0	50.4	16.6	0	0
30-Jun	13-0-46	25.2	3.3	0	11.6
7-Jul	33-0-0	50.4	16.6	0	0
7-Jul	13-0-46	25.2	3.3	0	11.6
14-Jul	33-0-0	50.4	16.6	0	0
14-Jul	13-0-46	25.2	3.3	0	11.6
21-Jul	33-0-0	50.4	16.6	0	0
21-Jul	13-0-46	25.2	3.3	0	11.6
28-Jul	33-0-0	50.4	16.6	0	0
28-Jul	13-0-46	25.2	3.3	0	11.6
4-Aug	33-0-0	50.4	16.6	0	0
4-Aug	13-0-46	31.5	4.1	0	14.5
11-Aug	33-0-0	50.4	16.6	0	0
11-Aug	13-0-46	31.5	4.1	0	14.5
18-Aug	33-0-0	50.4	16.6	0	0
18-Aug	13-0-46	31.5	4.1	0	14.5
25-Aug	33-0-0	50.4	16.6	0	0
25-Aug	13-0-46	31.5	4.1	0	14.5
1-Sep	33-0-0	50.4	16.6	0	0
1-Sep	13-0-46	25.2	3.3	0	11.6
8-Sep	33-0-0	50.4	16.6	0	0
8-Sep	13-0-46	25.2	3.3	0	11.6

Sources: 33-0-0 is ammonium nitrate; 12-61-0 is mono-ammonium phosphate; 13-0-46 is potassium nitrate

For the soil profile from 0.10 to 0.90 m, the soil water content at field capacity θ_F (0.33 bar) and soil water content at permanent wilting point θ_W (15 bar) had mean values of 0.23 and 0.11 $cm^3\ cm^{-3}$, respectively.

2.2. Drainage lysimeters and nutrient balance

Four drainage lysimeters, two per crop, were used for the present experiment. The mango and cherimoya lysimeters contained one tree of 15 years old and were 6 m^2 (2.0 m x 3.0 m) and 7.5 m^2 in area (3.0 m x 2.5 m), respectively, with 1.0 m deep bounded on the sides by nylon-reinforced polyethylene, and 35 m apart (Fig. 1).

Figure 1. Drainage lysimeters used for the study

The lysimeters were located on the terraces as a part of the orchard with mature trees with full production. Irrigation for each drainage lysimeter was applied by a combination of self-regulating emitters (4 L h^{-1}) in a double-line system and controlled automatically by a head-unit programmer and electro-hydraulic valves. The amounts of water applied per lysimeter were measured with flow meters. The experimental orchard, as well as the trees studied with the drainage lysimeters, was managed according to commercial practices in the area, using the conventional fertilization and routine cultivation techniques for diseases and insect control.

The main nutrient mass balance components were calculated from the data of this study by using the complete balance equation for a lysimeter:

$$S = F - H - L - G + M \qquad \text{(Eq. 1)}$$

where S represents the change in nutrient content during the time considered, F is the applied fertilizer rate, H the nutrient removal by fruit yield and pruning, L the loss by drainage water, G the gaseous losses, and M the minor transport paths, which include surface erosion.

2.3 Measurements, chemical analysis, and statistical evaluation

The drainage waters from the lysimeters were measured and the sampled weekly, promptly removed, refrigerated and transported to the laboratory for analysis. Each sample was analysed for NO_3-N, NH_4-N, PO_4^{3-}, and K concentration in accordance with standard methods for the examination of waters (APHA, AWWA, WPCF, 1995). The total nutrient transport was calculated weekly by multiplying the concentration by the volume of drainage water, whereupon these values were referred to surface unit.

Each year mango and cherimoya fruits from trees of the drainage lysimeters were harvested and samples were collected for the determination of nutrient removal (N, P, and K). Also, pruned debris was weighted, and to determine the total nutrient export in cherimoya once per year and in mango every two years. The K concentrations in the plant material were determined by atomic-absorption spectrophotometry (VARIAN SpectrAA 220FS) (Chapman and Pratt, 1961). The P was determined by the molybdenum-blue method (Fiske, 1952) and the total N by the Kjeldahl method (Bremmer, 1965).

Soil samples were collected from lysimeters (every 10 cm) and air dried and sieved through a 2 mm sieve to obtain in homogeneous fraction for subsequent chemical analysis according to standard methods (MAPA, 1994).

A one-way ANOVA was carried out to compare the means of leached nutrients in the drainage waters. Differences between individual means were tested using the Least Significant Difference test (LSD) at 5% level of significance.

2.4. Water balance and crop coefficient (Kc) estimation for mango and cherimoya lysimeters

Reference evapotranspiration (ET_0) was estimated by the Penman-Monteith equation, as recommended by Allen et al. (1998). Whether data used to calculate ET_0 were obtained from a weather station at the experimental station at 80 m of the drainage lysimeters. Crop coefficient (Kc) was calculated with the following equation:

$$Kc = ETc / ET_0 \qquad \text{(Eq. 2)}$$

where ETc is the actual evapotranspiration (mm) and ET_0 is the reference evapotranspiration (mm). Here ETc is estimated with the soil-water-balance equation of Hillel (1998):

$$ETc = Pef + I + U + R - Dw - \Delta S \quad \text{(Eq. 3)}$$

where Pef is the effective precipitation (mm), determined by USDA soil-conservation services method (Kuo et al., 2006; SCS, 1972), I the irrigation quota (mm), U the upward capillary flow into the root zone (mm), R the runoff (mm), Dw the downward drainage out of the root zone (mm) and ΔS the volumetric change of soil water stored in soil layer of 0-90 cm (mm).

The upward movement of water (U) in the loamy soil of the experimental site was estimated using Darcy's law (Fares and Alba, 1999; Kar et al., 2007; De Medeiros et al., 2005), indicating that it could be considered negligible in the water balance equation. The surface runoff (R) was also negligible during the two growing seasons because the lysimeters were located in the platform of terraces with 0% slope. The downward flow (Dw) was measured by drainage lysimeter. Soil-water content was measured twice weekly using the Frequency Domain Reflectometry (FDR) system, at 10, 20, 30, 40, 50, 60, 70, 80, and 90 cm soil depth. The FDR used was the commercial device with a hand-held capacitance probe (Diviner-Sentek Pty Ltd.). This instrument comprises a data display connected by cable to a portable probe rod with one sensor attached. Some measurements were made before and after irrigation and heavy-rain events.

The water-use efficiency was calculated using the following equation (Simsek et al., 2005; Zhang et al., 2004; 2007):

$$WUE = Y / ETc \qquad \text{(Eq. 4)}$$

where WUE is the water-use efficiency (kg ha^{-1} mm^{-1}), Y the fruit yield (kg ha^{-1}), and ETc is the total actual evapotranspiration over the growing season (mm).

4. Results and discussion

3.1. Drainage and nutrient leaching

Time-series graphs of lysimeters for effluent and rainfall each month is shown in Fig. 2a. On average, more percolate was registered from the two study crops during the irrigation period, especially in June, August, and September. Drainage volumes for these months represented the 50.4 and 43.3% of the total percolated volume for mango and cherimoya, respectively. Total average percolated water for mango and cherimoya was 69.2 and 50.4 mm, respectively (Fig. 2b).

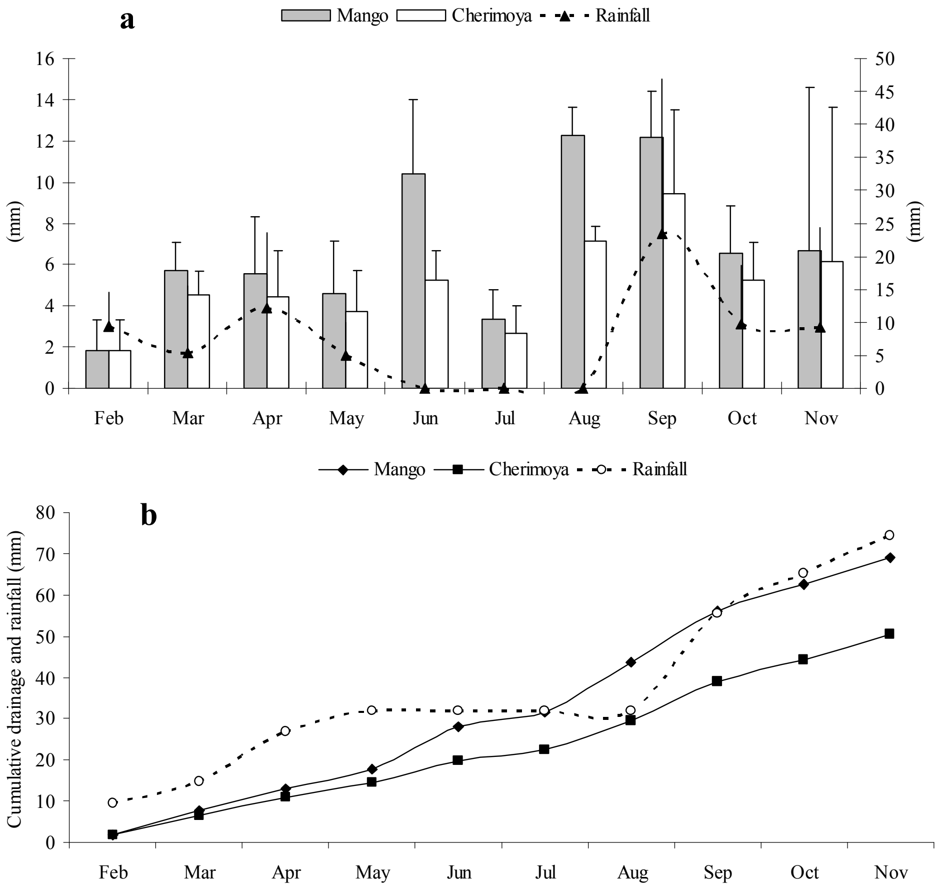

Figure 2. Average monthly drainage and rainfall water for the two study years (a) Cumulative average monthly drainage and rainfall for the study period (b). Vertical bars are standard deviation

The NO_3 concentration in the leachates during the study period ranged from 1.8 to 44.3 mg L^{-1} and from 23.0 to 51.0 mg L^{-1} for mango and cherimoya, respectively (Fig. 3). The average annual NO_3 concentrations for mango and cherimoya were 10.8 and 8.7 mg L^{-1}, respectively.

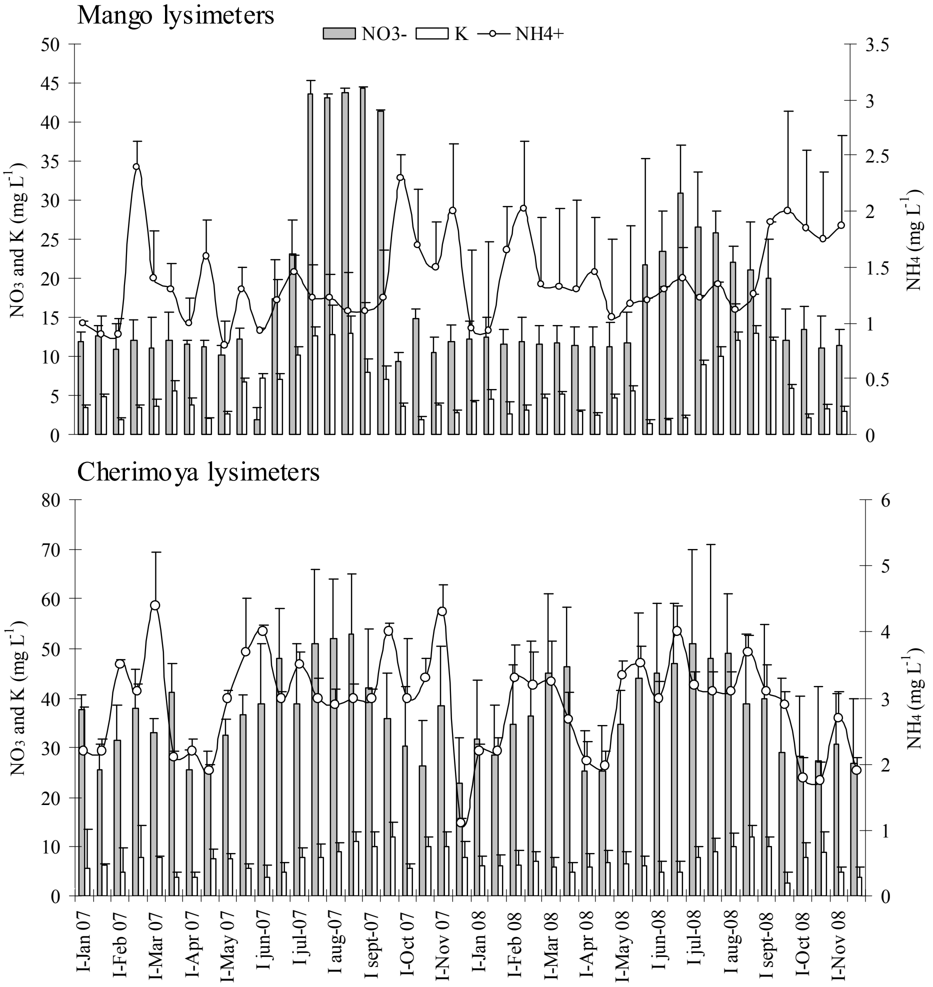

Figure 3. Average nitrate, ammonium and potassium concentration of leachates collected from the lysimeters. Vertical bars are standard deviation.

In general, the highest NO_3 concentration were found from June to September for both crops, ranging from 17.4 mg L^{-1} in June-07 to 43.6 mg L^{-1} in July-08 for mango and from 45.0 mg L^{-1} in June-08 to 53.0 mg L^{-1} in August-07 (Fig. 3). Since NO_3^- is not adsorbed by soils, it is likely that N-fertilizers are the major source of NO_3^-. Fertilization in mango based on phosphate mono-ammonium started from March, while fertilization by using ammonium nitrate took place from May to September, and this is probably the reason why NO_3^-

concentrations were higher for both crops from June to September. The average NO_3^- concentrations in mango lysimeters were higher during the first study year (19.1 and 16.2 mg L^{-1} for the first and the second year, respectively). However, average annual concentrations were similar for cherimoya during the two studied years (36.6 and 36.9 mg L^{-1} for the first and the second year, respectively). In most cases, the average monthly concentrations exceeded (in both crops) the 10 mg L^{-1} (limit for drinking water; U.S. EPA, 1976). The 25 mg L^{-1}, maximum limit for drinking water according to World Health Organization (WHO), was also surpassed during July, August, and September for mango and in most months for cherimoya (Fig. 3). Moreover, NO_3 concentrations in cherimoya were in some cases (July and August) above the 50 mg L^{-1}, maximum limit set by European directive for drinking water. In any case, both in cherimoya and mango lysimeters, NO_3 concentrations also exceeded the recommended limit (45 mg L^{-1}) for drinking water by the BIS (1991) and the World Health Organization (1993).

The ammonium concentration ranged from 0.9 to 2.4 and from 1.1 to 4.4 mg L^{-1} for mango and cherimoya lysimeters, respectively. The average annual NH_4 concentration for mango and cherimoya was 1.4 mg L^{-1} and 2.9 mg L^{-1}, respectively. Therefore, NH_4 concentration was two-fold higher for cherimoya than for mango. In this latter crop, the NH_4 concentrations were higher during February, October, and November of both study years, but lower during the summer months. However, no pattern was found in cherimoya lysimeters. Concentrations of NH_4^+ were consistently much lower than NO_3^-. The dominance of NO_3^- suggests that the dissolved nitrogen in the drainage water came mainly from N fertilizers (NH_4NO_3, $NH_4H_2PO_4$, KNO_3) applied to the terraces rather than from the soil. Moreover, the N in the drained solution was mainly in the form of NO_3^- because of the high solubility and lower affinity of its ions for the adsorption sites in the soil. Similar results have been reported by many authors (Kwong and Deville, 1984; Padovese, 1988, Southwick et al., 1995). However, the dynamics of nutrient flows in agricultural landscapes in our study zone have not been well documented, but many works in other countries concentrate on the impact of the human activity on nutrient losses by intensive agriculture (White et al., 1981) and excessive fertilization (Miller, 1979). This over-fertilization represented a high risk of pollution of NH_4^+, promoted by the low cation-exchange capacity of this soil that did not impede NH_4^+ leaching.

K concentrations in leachates from the lysimeters ranged from 1.8 to 13 mg L^{-1}, and from 2.7 to 12.1 mg L^{-1} for mango and cherimoya, respectively (Fig. 3). These K concentrations were relatively low probably due to the large uptake of K by these crops for fruit growth (Durán et al., 2006a; 2006b). The average annual K concentrations for mango and cherimoya were 5.6 and 6.8 mg L^{-1}, respectively. The highest concentrations were found during July, August, and September for both crops, reaching the highest values in August-07 and September-08 for mango (13.0 mg L^{-1}), and in September-07 and August-08 for cherimoya (12 mg L^{-1}) (Fig. 3). This was presumably due to the application of KNO_3, which was applied during these months (Table 1). During most months, the K concentration was less than 12 mg L^{-1} [the limit for drinking water established by the European Community, (EEC, 2000)].

Phosphate concentrations in water drained from lysimeters ranged from 0.07 to 0.5 mg L^{-1} for mango and from 0.12 to 0.68 mg L^{-1} for cherimoya (Fig. 4).

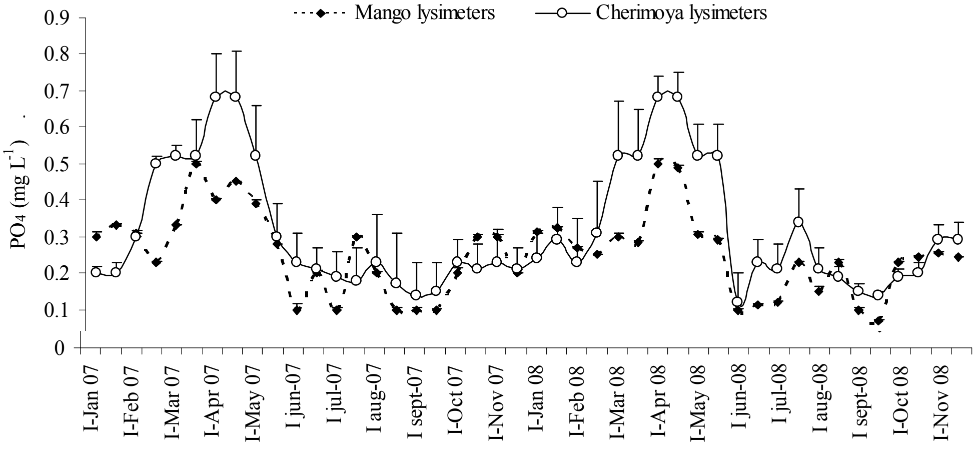

Figure 4. Average phosphate concentration of leachates collected from the lysimeters. Vertical bars are standard deviation.

Average annual PO_4 concentrations were 0.25 and 0.32 mg L^{-1} for mango and cherimoya, respectively. These values were in general low, probably due to the strong bond of phosphate with clay minerals and metal hydroxides (Matthess, 1982), mango and cherimoya lysimeters registering the highest PO_4 concentrations in April-07 and April-08 (0.45 and 0.50 mg L^{-1}, and 0.68 and 0.69 mg L^{-1}, respectively). When a soil is supplied with P, the soil adsorbing the constituents becomes increasingly saturated to the point that the P compounds became readily soluble. Hence, in intensive fruit cultivation under fertigation, the main types of P fertilizers can reach relatively high solubility. In this sense, average monthly PO_4^{3-} concentrations in drainage waters consistently exceeded the established limit concentration associated with eutrophication of surface water (0.01 mg P L^{-1}; Vollenweider, 1968), reaching 0.05 mg L^{-1} (U.S. EPA, 1976), 0.05-0.1 mg L^{-1} total P (the limit for the protection fresh water; ANZECC, 1992), and in some cases surpassing 0.3 mg L^{-1} according to Petrovic (1992). Also, there are several concentration limits for water, such as the European Community (Smeats and Amavis, 1981) which is 0.54 mg L^{-1}, which was surpassed only for cherimoya during April-07 and April-08 (0.68 and 0.67 mg L^{-1}, respectively). In this regard, Balogh and Walker (1992) reported low PO_4^{3-} concentrations in subsurface and runoff waters, since PO_4^{3-} is actively taken up by plants and readily sorbed and/or precipitated with Fe, Al, and Ca in soils, except for very coarse-texture soil, thus minimizing the potential for P mobility.

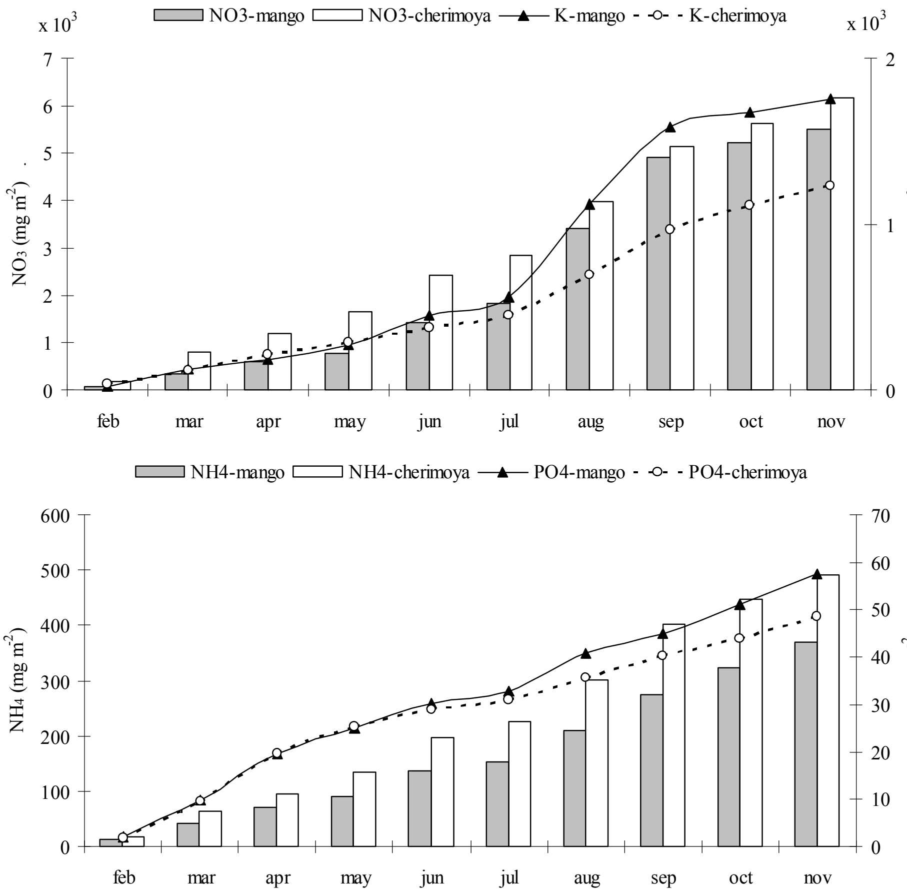

Figure 5. Cumulative nutrient losses for the study period from the drainage lysimeters

Fig. 5 shows the cumulative nutrient losses per area by leaching for the two crops. Total annual losses were 6,183 and 5,506 mg m^{-2} of NO_3-N, 492 and 370 mg m^{-2} of NH_4-N, 48.5 and 57.7 mg m^{-2} of PO_4-P and 1,779 and 1,235 mg m^{-2} of K for cherimoya and mango, respectively. The NO_3-N losses in cherimoya were slightly higher than in mango, this probably due to the higher rate of N fertilizer application in cherimoya than in mango (828.8

and 636.1 gr tree^{-1} yr^{-1}, respectively; Table 1). NH_4-N losses were approximately the same for both crops, but again losses in cherimoya were slightly higher than in mango (492 and 370 mg m^{-2}, respectively). However, PO_4-P losses were higher in mango than in cherimoya (57.7 and 48.5 mg m^{-2}, respectively) due to the higher application P fertiliser rates and also because of the lower remove from tree (fruits and pruning). An opposite situation occurred for K, with K losses being higher in cherimoya, despite the lower fertilization K rate and higher plant uptake when compared with mango.

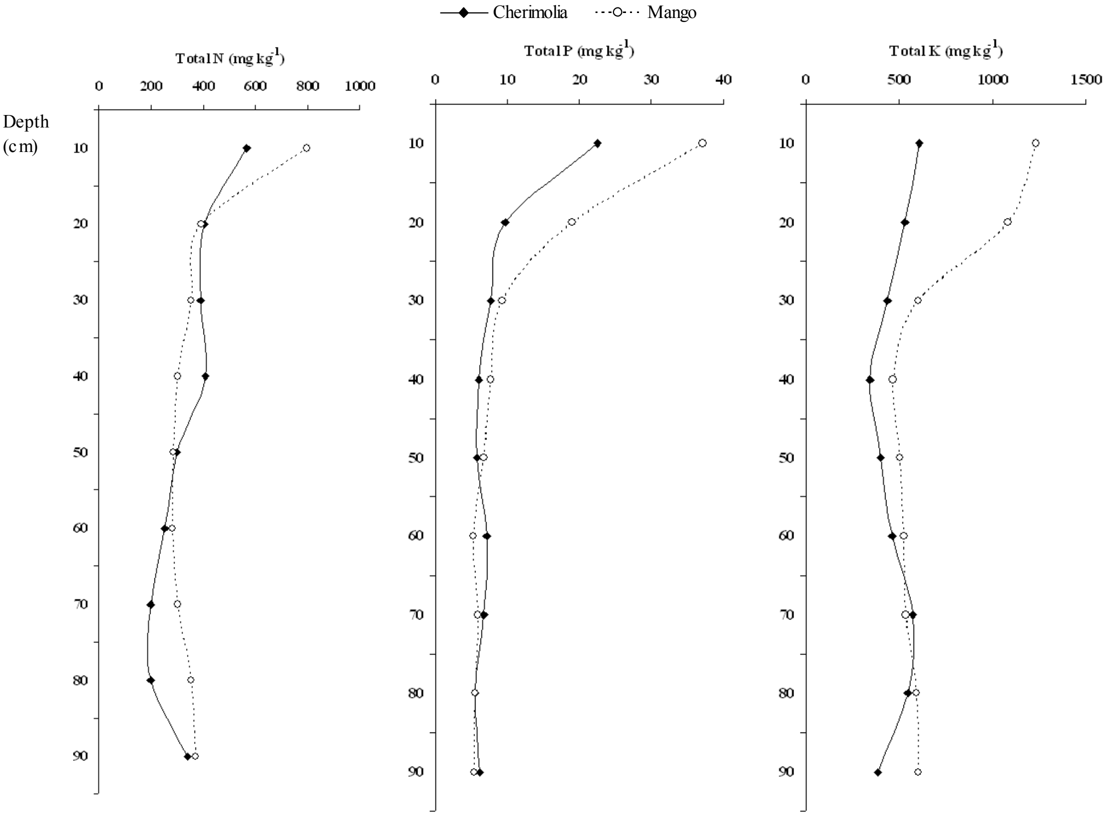

Figure 6. Total N, P, and K content at various soil depths from mango and cherimoya lysimeters

Fertilizer application caused an accumulation in total N, P, and K content at the soil surface (0-10 cm) for both crops (Fig. 6).

Total N in mango lysimeters proved higher than in cherimoya lysimeters at 0-20 cm, indicating an excess of fertilization in mango. N concentrations were much higher in 0-20 cm than for the rest of the profile (net accumulation on surface). Similar results were found by Wong et al. (1998) in a fertilization study on golf fairways and greens. With respect to P, there was again a strong dependency of the concentration on the depth: for both crops the P concentration was much higher at 0-20 cm of the profile. For total P, the distribution was similar to that of N for the soil lysimeters studied (Fig. 5); that is, total P was higher in mango lysimeters than in cherimoya ones at 0-50 cm depth. This was presumably due to the higher fertilizer rates of N and P in mango.

3.2. Nutrient budget

Despite the inherent variability in data from the different N sources in this type of agroecosystem, we have estimated the N, P, and K budgets for these fertilised drainage lysimeters, according to Eq. 1.

For our study and experimental conditions, we considered the gaseous losses (G) and minor paths of transport (M) parameters to be equal zero. In a system in a year-to-year stationary state, S would be zero (Prunty and Greenland, 1997). Therefore, we have estimated an approximate net NPK soil accumulation (soil residual) comparing the existing N, P, and K concentrations at 0-10 cm with those found at 20-30 cm lysimeter soil depth. The nutrient removal by fruit yield and pruning for both crops is shown in Table 2, which represents the H value for nutrient balance.

Table 2. Nutrient removal by fruit yield and pruning material from mango and cherimoya trees by study period

Plant Material	N (kg ha^{-1})	% of applied N	P (kg ha^{-1})	% of applied P	K (kg ha^{-1})	% of applied K
Cherimoya lysimeters						
Pruning	50.8	21.9	7.6	11.1	26.8	34.7
Fruit yield	76.4	32.9	5.5	8.1	22.6	29.3
Mango lysimeters						
Pruning	23.6	5.8	2.4	1.4	12.7	9.1
Fruit yield	30.2	7.5	3.3	1.9	27.8	20.0

Also, the L values for mango and cherimoya lysimeters are listed in Table 3. The N inputs from fixation and precipitation were not included in the budget because we considered them to be negligible in comparison to fertilizer inputs.

Table 3. Nutrient losses from the drainage lysimeters for the two studied irrigation seasons

	Total applied nutrient			Soluble nutrients in drainage waters										
Lysimeter	N	P	K	NO_3	N	% of applied N	NH_4	N	% of applied N	PO_4	P	% of applied P	K	% of applied K
		(kg ha^{-1})		(kg ha^{-1})			(kg ha^{-1})			(kg ha^{-1})			(kg ha^{-1})	
Cherimoya	232.1	68.3	77.3	61.8 a	14.0 a	6.0 a	4.9 a	3.8 a	1.6 a	0.49 a	0.16 a	0.23 a	12.3 a	16.0 a
				(± 17.2)	(± 3.8)	(± 1.6)	(± 1.2)	(± 0.9)	(± 0.4)	(± 0.14)	(± 0.05)	(± 0.07)	(± 2.1)	(± 2.7)
Mango	402.0	172.9	139.2	56.0 a	12.4 a	3.1b	3.7 a	2.9 a	0.7 b	0.58 a	0.19 a	0.11 b	17.6 b	12.6 b
				(± 12.6)	(± 2.8)	(± 0.7)	(± 0.9)	(± 0.7)	(± 0.2)	(± 0.13)	(± 0.04)	(± 0.02)	(± 1.7)	(± 1.2)

(± Standard deviation); values followed by the same letter within the same column do not differ significantly at 5% level according to the least significant difference test (LSD).

The N, P, and K soil residual contents are also shown in Table 4, which summarizes the complete balance for each of the study crops as percentage of the initial applied nutrients. The macronutrient balance showed am excess of N, P, and K fertilizer applied (F) over removal by fruit yield and pruning (H) and leaching (L), especially in mango.

Table 4. Nutrient budget for a drainage lysimeters with mango and cherimoya trees

	N		P		K	
			(%)			
	Mango	Cherimoya	Mango	Cherimoya	Mango	Cherimoya
Fruit harvest	7.5	32.9	1.9	8.1	20.0	29.3
Wood pruning	5.8	21.9	1.4	11.1	9.1	34.7
Leachated	3.8	7.67	0.11	0.23	12.6	16.0
Soil residual	48.0	13.3	47.0	61.0	46.6	6.7
Others	34.9	24.2	49.6	19.6	11.7	13.3

The average fruit yield according to the mango and cherimoya lysimeters was 24.3 and 36.0 kg per tree. With respect to mango, N, P, and K removed by pruning per year represented 5.8, 1.4, and 9.1%, respectively (Table 2). On the other hand, the N, P, and K removed by mango fruits in relation to the total applied fertilizer were 7.5, 1.9, and 20.0 %, respectively. Therefore, according to balance of nutrients from lysimeter data, only 13.3, 3.3, and 29.1% of N, P and K, respectively, was taken up by mango trees annually. Nutrient losses in the leachates of the mango lysimeters represented 6.6% for inorganic N ($NO_3^- + NH_4^+$), 0.23% for P, and 16% for K (Table 3). Soil N, P, and K residual accounted for a 48.0, 47.0, and 46.6%, respectively (Table 4). Thus, conventional application rates of fertilizers were excessive in mango orchards, residues accumulating in the upper soil layers with high risk of transport, especially during the rainy period.

The percentage of N, P, and K removal by cherimoya tree pruning was, respectively, 21.9, 11.1, and 34.7%, and by fruit yield of 32.9, 8.1, and 29.3% (Table 2). Nutrient leaching represented 7.6% for N ($NO_3^- + NH_4^+$), 0.23% for P, and 16.6% for K (Table 3). Consequently, the, 54.8 % of the applied N was taken up by the cherimoya tree, 7.7% was leached and 24.2% was not accounted for by the methods used. However, only 19.2% of the P was removed by plant uptake, and 0.23% was leached. Thus, there was a high leaching potential of P.

With respect to K, 64% of this applied nutrient was utilized by the cherimoya tree, and therefore the amount of K from fertilization was slightly higher than the nutritional requirements of the tree (Table 3). For cherimoya and mango, respectively, the K leached was 12.3 and 17.6 kg ha^{-1}, representing some 16 and 13% of the K fertilizer applied, these values differing significantly from each other. Statistical differences in leachated nutrients are shown in Table 3. Nutrient losses in drainage water expressed as a percentage of applied fertilizer differed significantly between the two study crops. In this sense, N, P, and K losses expressed as a percentage of the applied nutrients were significantly higher in cherimoya than those found in mango.

These values were relatively high, when compared with other budget-lysimeter studies made for other crops. In this context, Oliveira et al. (2002) reported on K leachates which represented some 8% of the applied K fertilizer in sugarcane while Wong et al. (1992) recorded K concentrations in leachates that represented less than 10% of the exchangeable K of the soil and applied fertilizer. Our high K contents in water drainage from the lysimeters could be due to the low clay content of the soil and low cation -exchange capacity, this situation leading to less K adsorption by soil in the study area.

3.3. Estimation of crop coefficients (Kc)

Fig. 7 shows the changes of the average crop coefficient (*Kc*) for mango and cherimoya over two monitoring seasons estimated by the water balance from experimental drainage lysimeters. The crop coefficients presented at three main growing stages (flowering, fruit set, and fruit growth) were fitted by a polynomial function (between Julian days and *Kc*), as reflected in Fig. 7. The period of flowering, fruit set, and fruit growth for mango was about 49, 50, and 77 days, and the average crop coefficient values were 0.56, 0.71, and 0.61, respectively. Similar for cherimoya trees the duration of the flowering, fruit set, and fruit growth was about 32, 41, and 86 days, and the average crop-coefficient values were 0.62, 0.65, and 0.50, respectively.

The *Kc* values for both mango and cherimoya trees were not available, especially in subtropical areas of orchard terraces. However, the results of crop coefficients found in this study were consistent with those reported in literature (FAO, 1998; da Silva et al., 2009).

After fruit harvest, crop coefficient for mango and cherimoya trees decreased quickly to 0.26 and 0.21, respectively. In this regard, the *Kc* was related closely to crop type and management practice, which may influence plant-development rate and ground coverage (Allen et al., 1998; Williams and Ayars, 2005) throughout the vegetative growth.

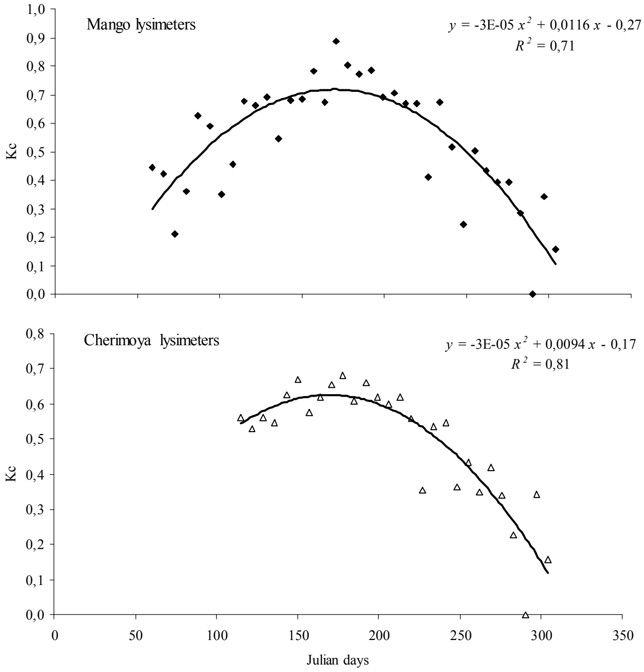

Figure 7. Crop coefficient as a function of Julian days for mango and cherimoya trees growing in an orchard terraces during two-year monitoring growing season (2007-2008).

Fig. 8 shows the average *ETc* and *ET0* for mango and cherimoya trees during the two monitoring years. Generally, the *ETc* rate for both irrigated crops was higher during the summer months, especially in July, with the maximum monthly average *ETc* for mango and cherimoya being 5.7 mm day^{-1} or 96 L tree^{-1} day^{-1} (600 trees per ha) and 4.6 mm day^{-1} or 164.7 L tree^{-1} day^{-1} (280 trees per ha), respectively. The average annual value of the crop coefficients (*Kc*) for mango and cherimoya trees during the irrigation period (March-October for mango and May-October for cherimoya) was 0.58 and 0.55, respectively. Monthly *Kc* values for mango trees also showed a clear seasonal trend, with maximum values in summer (0.65), intermediate values in spring and autumn (0.56 and 0.43, respectively). And the *Kc* values for cherimoya trees were maximum in summer (0.57), and intermediate in spring and autumn (0.48 and 0.39, respectively). These values provide a useful base for designing the irrigation timetable in drip-irrigation systems, for mango and cherimoya orchards.

On the other hand, by taking into account that, in the study area for mango and cherimoya, about 600 and 280 trees per ha are distributed in orchard terraces, with an average yield of

24.3 and 36.0 kg per tree from the lysimeters. Therefore, the potential average yield for mango and cherimoya was 14.6 and 10.0 t ha^{-1} yr^{-1}, respectively.

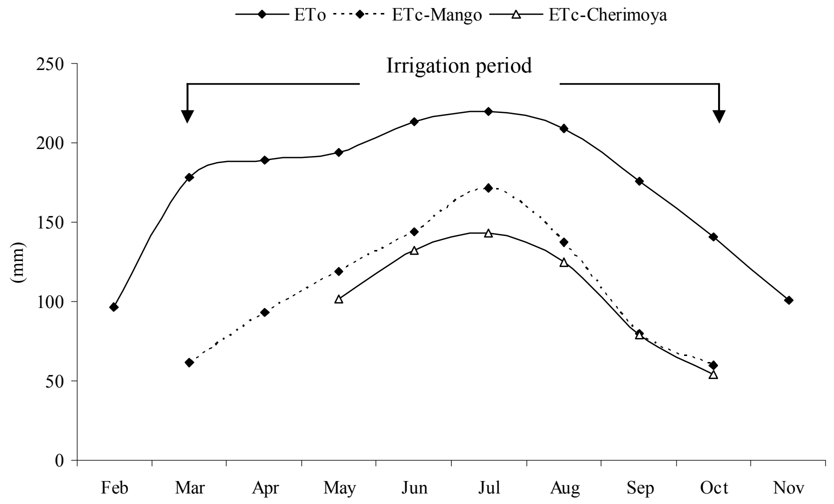

Figure 8. Monthly average of reference and actual evapotranspiration for mango and cherimoya trees

Consequently, the average WUE in the mango and cherimoya orchards in our subtropical area was 21.2 and 14.0 kg ha^{-1} mm^{-1}, respectively. These results are lower than reported by Da Silva (2009) for mango in a tropical Brazilian region with WUE of 70.5 kg ha^{-1} mm^{-1} and yield of 31.1 t ha^{-1}.

4. Conclusions

Subtropical fruit production in the south-eastern Spain is feasible under precision management of irrigated crops. This study has demonstrated that fertilisers in this area are applied in excess, leading to potential groundwater-pollution risk. The optimisation of fertilizer input is crucial in order protect the environment, as application rates should be close to removal rates by fruit yield and pruning. However, conventional agriculture applies more N, P, and K than necessary. Past instances of groundwater contamination under subtropical crops cultivation are not well documented in the study area. An understanding of that way in which NPK losses can occur provides practical information concerning rational fertilizer application rates, which are needed for a proper nutritional strategy of mango and cherimoya trees. Therefore, continuous efforts should be made to advise the farmers about the optimal use of fertilizers with respect to crop requirements.

The Kc values for mango and cherimoya offer a useful tool for improving irrigation management, adjusting irrigation volume and frequency to crop water demand under subtropical Mediterranean climate.

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Capítulo V

Optimization of drip irrigation management for mango (*Mangifera indic*a L. cv. Osteen) in orchard terraces: effect on fruit yield and quality, tree growth, and mineral status

Aceptado en *Scientia Horticulturae*

Optimization of drip irrigation management for mango (*Mangifera indica* L. cv. Osteen) in orchard terraces: effect on fruit yield and quality, tree growth, and mineral status

Rodríguez Pleguezuelo, C.R.[1*], Durán Zuazo, V.H.[2], Martín Peinado, F.J.[3],
Franco Tarifa, D.[4], Espejo Arenas, A.B.[3]

[1]IFAPA Centro Camino de Purchil. Aptdo. 2027-18080 Granada, Spain.
Phone: (+34) 958 895 255; (+34) 647 199 854. Fax: (+34) 958 895 202
*corresponding author email: crocio.rodriguez@juntadeandalucia.es
[2]IFAPA Centro Las Torres-Tomejil. Crtra Sevilla-Cazalla, km 12.2; 41200 Alcalá del Rio (Sevilla) Spain.
[3]Departamento de Edafología y Química Agrícola, Universidad de Granada, C/Severo Ochoa s/n, 18071-Granada, Spain
[4]Finca "El Zahorí". Patronato de Cultivos Subtropicales Plaza de la Constitución 1, Almuñécar (Granada), Spain

ABSTRACT

Mango (*Mangifera indica* L.) is one of the crops with a major economic importance in the provinces of Málaga and Granada (SE Spain). Fruit development takes place during the driest season; therefore it is necessary to irrigate mango trees to ensure high yields and good quality. A field experiment on mango trees was designed with objective to search optimum irrigation scheduling during three years. Four irrigation treatments were applied: T1, T2, T3 and T4 each received 33, 50, 75 and 100% ETc, respectively. The response of fruit yield, number of fruits, fruit size and quality parameters (Total soluble solids and titratable acidity), and macro- and micronutrients in leaves and fruits were determined, as well as soil water dynamics. From the results of the experiment, the T2 was the most appropriate irrigation strategy since it reached the highest yield per tree (30.7 kg tree^{-1}) and water use efficiency of 7.14 kg m^{-3}. However, the fruit size was higher for T3 and T4, since they reached significantly higher length and width. Significant second degree polynomial regressions were found between mango yield and water irrigation amounts. The T4 registered the highest soil water content for the whole profile. Water was also highest at 30-50 cm depths for all the irrigation treatments and it tended to low at 10 and 70 cm depth. The total soluble solids were affected by irrigation treatment only during one year, being highest in T1 and T2. Also, the titratable acidity was not affected by irrigation. Macro- and micronutrient concentrations in leaves were affected by irrigation regimes only for P, Mg and Mn. In addition, nutrients in mango fruits were generally higher for T3 and T4. Thus, T2 (50% Etc) irrigation treatment is recommended for mango in order to attain higher yields, which have a significant impact in improving the water use efficiency.

Keywords: mango, water use efficiency, terrace orchards, fruit yield.

1. Introduction

Mango belongs to the genus *Mangifera* of the family Anacardiaceae. The genus *Mangifera* contains several species of edible fruits, but the most commonly known belong to *Mangifera indica*. Mango fruit is a very popular fruit all over the world due to its bright colour, characteristic taste and nutritional value, being native from the Indo-Burmese region (Malik and Singh, 2006). Mango currently ranks fifth in total production among major fruit crops world wide. The world production of mangoes is estimated to be over 28.51 million tones per year and it is grown commercially in more than 90 countries; Asia produces 77% of the world yield, America 13% and Africa 9%. In 2005, global exports reached 912,853 tones, for a total of 543.10 million dollars (FAOSTAT 2007). Spain is the main EU producer of tropical and subtropical fruit. In this sense, in 2000, the EU imported a total of 6,647 tones of mangos from Spain (from a total of 117,102 tones imported globally) (Cohen et al., 2001). Concretely, in Spain, cultivation is feasible primarily in the provinces of Granada and Málaga, with some 900 ha of mango orchards soon to exceed a yield of 6,000 t year^{-1}, which most of them are Florida cultivars (Cambell and Cambell, 1993). In this area, the most extensively produced and commercial cultivar is cv. Osteen, this having an average weight of 527.08 g, length of 127.14 mm width of 90.70 mm and pulp-seed ratio 88.22% (Calatrava et al., 1992)

Meanwhile, the reduction availability of fresh water is getting a worldwide problem, mainly in the Mediterranean basin, where the climate is characterised by dry summer with high temperatures and evapotranspiration and precipitation commonly concentrated in autumn and winter but largely unpredictable in amount and spatiotemporal distribution (Joffre et al., 2001). In this context, the use of water in Spain by agriculture accounts for an 80% of the total (MMA, 2000). Therefore, adopting water-saving strategies for efficient use of water by agriculture is becoming increasingly important.

In this context, in some areas of the coast of Granada the aquifers have been damaged by saltwater intrusion in the past decade. Increasing subtropical irrigated agriculture together with the expanding tourism lead to an important increase in the consumption of water during the summer. This situation is particularly alarming, since these "population peaks" occurs at the same time that the lowest recharge of the main aquifer, which is called "Rio Verde". As a consequence, salt water intrusion infiltrates in this aquifer and promotes declining water quality. Many studies in the area have been developed to control these phenomena (Benavente et al., 1984; Molina et al., 1988; Calvache and Pulido, 1990) and its impact in the crops (Durán et al., 2004). Irrigation management is crucial to the production of fruit quality; being water inputs must be geared to tree water requirements, soil factors and fruit physiological requirements. However, few studies have been carried out in the area respecting to the optimal water supply for subtropical agriculture. Furthermore, the maintenance of adequate soil water content in this type of crops is necessary to support optimum plant growth and fruit yield, therefore, an understanding of the soil water content is important to manage irrigation properly.

Flowering and fruit development in mango takes place in the coast of Granada during the dry season and farmers have to irrigate trees to guarantee high yields. Irrigation requirement and its effect on mineral nutrition in mango is still not well investigated (de Azevedo et al., 2003; Spreer et al., 2008), specially under subtropical climate. On the other side, knowledge of the nutrient elements present in leaves during different stages of the cycle of growth and development is essential for determining a tree's nutritional demands and thus establishing optimal fertilizer application at a specific developmental stage (Eswara, 1981; Benton and Jones, 1985).

Therefore, the objective of this study was to assess the response of mango trees to varying drip irrigation regimes on fruit yield and quality, tree growth, soil water dynamics, and mineral status under Mediterranean subtropical climate.

2. Materials and methods

2.1. Experimental site

The field experiment was carried out in 2006-2008 at the experimental farm "El Zahorí" near Granada (South-eastern Spain) (36º48´00´´N, 3º38´0´´W) and at an elevation of 195 m a.s.l. The study terrace, representative of those commonly found in the area, is a reverse sloped bench-terrace type measuring 160-180 m long. The platform had a single row of mango trees

(*Mangifera indica* L. cv. Osteen) spaced 3 m apart. Under experimental conditions, a cultivated hectare of mango trees on steeply sloped lands (65º) would have 18 terraces (spaced about 5 m) 100 long, with an average of 600 trees per ha. Local temperatures are subtropical to semi-hot within the Mediterranean climatic category (Elias and Ruiz, 1977). The average annual rainfall in the study area is 449.0 mm and average temperature is 20.8 ºC. The soils of the zone are Typical Xerorthent (Soil Survey Staff, 1999), with 684 g kg^{-1} of sand, 235 g kg^{-1} of silt and 81 g kg^{-1} of clay, containing 9.4 g kg^{-1} of organic matter, and 0.7 g kg^{-1} of N, with 14.6 mg kg^{-1} P, and 178.7 mg kg^{-1} assimilable K (MAPA, 1994).

2.2. Plant material and experimental design

A mature orchard of 12-years old mango trees were selected as experimental trees (*Mangifera indica* cv. Osteen) being healthy and uniform in size. The whole growing season of mango trees in the area included the following phenological stages: dormancy (November-February), flowering (March-April), fruit set (May-June), fruit growth (July-September), and harvest (October-November).

Irrigation treatments included the following irrigation regimes T1, T2, T3 and T4 each received 33, 50, 75 and 100% of ETc, respectively. Control T4 received 100% of the irrigation volume required to meet their crop evapotranspiration demand for the irrigation period. The Penman-Monteith method (Allen et al, 1998) was used to determine reference evapotranspiration (ET_0) and crop coefficients K_c with adjustment of tree size (Fereres and Castel, 1981; Girona et al., 2002) were estimated from a drainage lysimeters, which are located in the same orchard. Each treatment was applied by combination of several self-regulating emitters (4 and 8 L h^{-1}) in a double-line system. Irrigation was controlled automatically by a head-unit programmer and electro-hydraulic valves. The amounts of water applied per treatment were measured with flow meters. The experiment was completely randomized block-design with 3 replications per treatment. Each plot had eight trees per row. The four central trees of the rows were used for fruit yield and tree size measurements and the other four trees served as border trees. The experimental orchard was managed according to commercial practices in the area, with the same fertilization (240 g N, 71 g P_2O_5 and 212 g K_2O) and routine cultivation techniques for diseases and insect control were used.

2.3. Field measurements, chemical analysis and statistical evaluation

Harvest occurred on October-November of each year and total fruit yield per tree was registered for each treatment. In the second and third season (2007-2008), 25 fruits per tree were collected to measure vertical and horizontal diameters with a vernier calliper. Also, 10 fruits were selected randomly to evaluate skin, pulp and seed weight percentage. We also determined titratable acidity from fruit juice titrating against NaOH 0.05 N using phenolphtalein as the indicator (AOAC, 1980). Total soluble solids (TSS) (ºBrix) were measured by direct reading in a refractometer (Eclipse, Bellinghan and Stanley, Ltd).

Also, height, canopy diameter and trunk circumference were measured 15 cm above the bud union in grafted trees. Canopy volume was calculated using the equation for one-half of a proplate spheroid (Castle and Phillips, 1980; Avilan et al., 1997)

$$CV = 4/3 * \Pi * r^2 * 1/2 * H \qquad \text{(Eq. 1)}$$

where CV = Canopy volume; r = canopy radio; H = canopy height.

Trunk circumference was converted into trunk cross-sectional area (TCSA) by the following equation:

$$TCSA = C^2 / 4\Pi \qquad \text{(Eq 2)}$$

where C = trunk circumference (cm)

Yield efficiency was estimated dividing fruit yield by canopy volume and by TCSA. Water use efficiency (WUE) was calculated as fresh mango yield divided by total seasonal irrigation water applied (Howel et al., 1990).

The soil-water content (θv) during the irrigation season was determined using the Frequency Domain Reflectometry (FDR) system, at 10, 20, 30, 40, 50, 60 and 70 cm soil depth. The FDR used was the commercial device with a hand-held capacitance probe (Diviner-Sentek Pty Ltd.). This instrument comprises a data display connected by cable to a portable probe rod with one sensor attached. This method includes the soil as part of a capacitor, in which the permanent dipoles of water are aligned by an electric field and become polarized. The dielectric dipoles respond to the frequency of the electric field. The response is a function of molecular inertia, the binding forces, and the frequency of the electric field (Dean et al., 1987; Gardner et al., 1991). We calibrated the device under field conditions and the data points collected in the calibration procedure were curve fit with the equation according to technical specifications (Diviner-Sentek Pty Ltd.).

Leaves and fruits were chemically analyzed after washing and rinsing with distilled water and drying at 70 and 50ºC for 48 and 96 h, respectively. The K, Ca, Mg, Fe, Zn, Mn, and Cu concentrations in the plant material were determined by atomic-absorption spectrophotometry (Chapman and Pratt, 1961). The P concentration was determined by the molybdenum-blue method (Fiske, 1952), and the total N by the Kjeldahl method (Bremner, 1965).

Data of fruit yield in each year, WUE, fruit quality and mineral status in leaves and fruits were evaluated by analysis of variance and means were separated by Tukey's test ($p < 0.05$). Also, second degree polynomial functions were adjusted between fruit yield and irrigation water amounts. Linear regression between yield and number of fruits per tree and fruit size were also established.

3. Results and discussion

3.1. Fruit yield, WUE, tree size, and soil water dynamics

Table 1 shows the results for average fruit yield, number of fruits per tree, fruit weight, and WUE for each treatment.

Table 1. Irrigation and fruit yield for the study period.

Irrigation treatment	Irrigation (m^3 tree^{-1})	Fruit yield (kg tree^{-1})	Num. Fruits tree^{-1}	Fruit weight (g)	WUE (kg m^{-3})	Length (cm)	Width (cm)
T1	2.80	16.0a	28.3a	536.9a	5.7ab	13.1a	8.6a
T2	4.30	30.7b	53.7b	568.5ab	7.1b	13.6ab	8.9a
T3	5.76	22.5ab	36.5ab	626.8bc	3.9a	13.8b	9.1ab
T4	6.48	22.3ab	38.5ab	648.4c	3.4a	14.1b	9.5b
Year							
2006		19.6a	38.4ab	522.8a	4.4a	nd	nd
2007		20.1a	29.4a	680.1c	4.6a	14.3a	9.7a
2008		28.9b	49.9b	582.5b	6.1a	13.0b	8.3b
ANOVA							
IT		*	*	*	*	*	*
Year		*	*	*	ns	*	*
Interaction		ns	ns	ns	ns	*	ns

IT, Irrigation Treatment, WUE, Water Use Efficiency. Different letters within the same column are statistical different by Tukey's test ($p < 0.05$); *, significant at $p < 0.05$; ns, not significant; nd, not data.

Over the three studied years, average yields per tree were 16.0, 30.7, 22.5 and 22.3 kg tree^{-1}. By taking into account that in this study area about 600 trees per ha are distributed in orchard terraces, the average yield for T1, T2, T3, and T4 was 9.6, 18.4, 13.5 and 13.4 t ha^{-1} yr^{-1}, respectively. The T2 reached the highest average yield per tree, being significant in comparison with the remaining treatments. In this sense, T2 produced 1.9, 1.4 and 1.4-times more fruit yield than T1, T3 and T4, respectively. By comparing the years of study, the third one registered the highest fruit yield. Yields in this experiment were generally much lower than those obtained by Avilán et al. (1974) in Venezuela for cv. Kent and Smith (378-868 kg tree^{-1}). It must be taken into consideration that the coast of Granada and Málaga represent the climatic limit for commercially viable mango performance, therefore, tree sizes and yields are much lower (Durán et al., 2006), but at high-density planting. In this context, Spreer et al. (2008) obtained similar yields for cv. Chok Anan (13.5-32.8 kg tree^{-1}) in an experiment of partial root drying and regulated deficit irrigation, respectively. Regarding to the average number of fruits per tree, T2 produced always higher amounts of fruits than other treatments. However, in this study, average fruit weight reached the highest in T4, which differed significantly from the other treatments (Table 1). Therefore, differences in yield were influenced by the number of fruits as well as by the fruit size. However, fruit yield was mainly correlated to the number of harvested fruits ($y = 0.50x + 3.36$; $R^2 = 0.91$) and not with the average fruit weight ($R^2 = 0.04$), agreeing with the results found by Spreer et al. (2008). In relation to average fruit weight, ranged from 536.9 to 648.4 g for T1 and T4, respectively. Therefore, mean fruit weight increased with higher irrigation amounts, being the T4 produced the heaviest fruits, differing significantly from the remaining treatments.

The water use efficiency values were significantly influenced by the irrigation treatment ($p < 0.05$), ranging from 3.4 kg m^{-3} in T4, to 7.1 kg m^{-3} in T2 (Table 1). The WUE was significantly higher in T2 than in the rest of treatments. Therefore, WUE values were lower with increasing irrigation water amounts. Similar results for mango were found in irrigation trials by Pavel and Williams (2004) and Spreer et al. (2008), as well as for many other types of crops (Sezen et al., 2006; Singh et al., 2007; Dagdelen et al., 2009). Therefore, increasing water amount in mango cv. Osteen did not implicate higher yields and WUE, as it was also pointed out by da Campos et al. (2008) with mango cv. Tommy Atkins. In this sense, respecting to the regression between fruit yield of the studied treatments and the overall water consumption from irrigation, we obtained a good fit to a binomial yield function for the three studied years (Fig. 1).

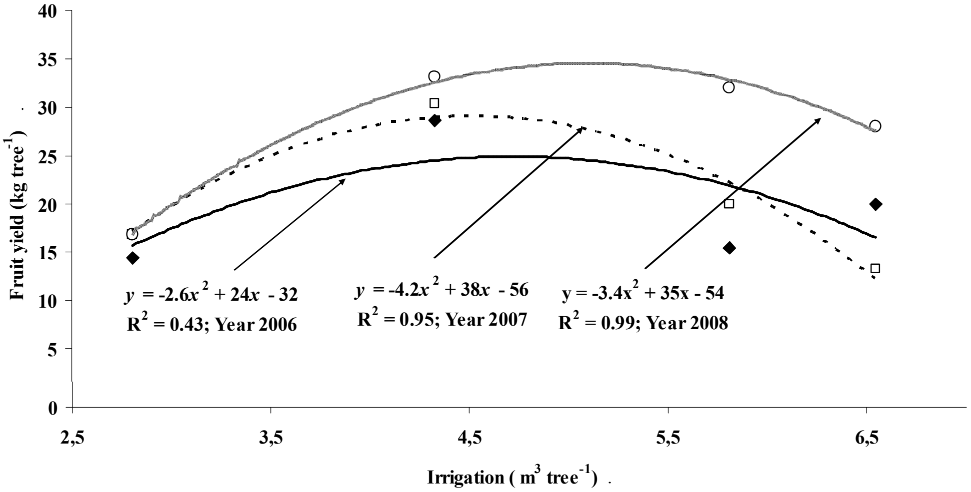

Figure 1. Production functions for the study period (2006-2008) comparing fruit yield and applied water. Each point represents average of 16 studied trees at different irrigation regimes.

By taking into account the three studied years, the fit to a binomial function was also good ($y = -3.42x^2 + 32.34x - 47.13$; $R^2 = 0.85$). As it can be seen, optimum level of irrigation would be approximately from 4.5 to 5.5 m^3 tree^{-1}, which would correspond mainly to T2. This type of binomial functions relating yield and irrigation water has also been established for other types of crops (Sezen et al, 2006; Gattan et al., 2006) as well as for mango (Spreer et al., 2008).

Thus, T2 showed to be the optimum irrigation treatment in our experiment, since it obtained the highest average yield, number of fruits per tree and WUE (30.7 kg, 53.7 fruits tree^{-1}, and 7.14 kg m^{-3}); on the opposite side, T1 obtained the lowest average yield and number of fruits per tree and the minimum WUE was recorded from T4.

Table 2 shows the results for tree size in the four studied treatments, revealing that T4 had the highest TCSA, and one of the highest tree height and canopy volume (136 cm^2, 2.9 m and 13.9 m^3, respectively). Therefore, the higher irrigation amount in T4 was invested into vegetative growth rather than in fruit yield. By contrast, the T1 reached the lowest canopy diameter, tree height and canopy volume (2.6 m, 2.5 m, and 8.9 m^3, respectively). In terms of yield efficiency (g cm^{-2}) were recorded the following tendency: T3 > T2 > T1 > T4, however, the differences were not statistically significant (Table 2). Meanwhile, yield efficiency expressed as kg m^{-3}, presented the following pattern: T1 = T2 ≈ T3 > T4. Therefore, T4 was again the least efficient treatment in relation to the yield efficiency for tree size.

Table 2. Tree size and yield efficiency for the irrigation treatments

Irrigation treatment	TCSA (cm^2)	Canopy diameter (m)	Tree height (m)	Canopy volume (m^3)	Yield efficiency	
					($g\ cm^{-2}$)	($kg\ m^{-3}$)
T1	103.4ab	2.6a	2.5a	8.9a	215.2a	2.6a
T2	127.2bc	3.0b	2.9b	13.8b	219.8a	2.5a
T3	96.0a	3.0ab	2.8ab	13.7b	268.8a	1.7ab
T4	136.0c	3.0ab	2.9b	13.9b	171.2a	1.3b
Year						
2007	101.8a	2.8a	2.7a	11.4a	215.7a	1.8a
2008	129.6b	3.0b	2.8b	13.8b	221.8b	2.2a
ANOVA						
IT	*	*	*	*	ns	*
Year	*	*	*	*	ns	ns
Interaction	ns	ns	ns	ns	ns	ns

IT, Irrigation Treatment, WUE, Water Use Efficiency; TCSA, Trunk Cross Sectional Area; Different letters within the same column are statistical different by Tukey´s test ($p < 0.05$); *, significant at $p < 0.05$; ns, not significant.

The total applied water in the orchard terraces for T1, T2, T3, and T4 was of 1,680, 2,580, 3,480, and 3,900 $m^3\ ha^{-1}$, respectively. Therefore, T2 saved irrigation water respect to T3 and T4 was of 26 and 34%, respectively, improving the fruit yield.

Table 3 presents the results of the ANOVA analysis for volumetric water content (θ_v) at each soil depth comparing the studied irrigation treatments among them. As it can be shown, T4 differed significantly from the remaining treatments, registering at all depths the highest soil water content. The θ_v in T2 and T3 did not differ significantly from each other at all the registered depths, excepting for 10 cm, where T2 reached higher θ_v than T3. Soil water content for the entire profile and each treatment was generally higher for 30-50 cm depth, and then it tended to be lower at 60-70 cm depth (Fig. 2), excepting for T4, which registered a peak in θ_v at 60 cm depth.

Table 3. Average volumetric soil-water content at different soil depths.

Depth	Volumetric soil-water content (%)			
(cm)	T1	T2	T3	T4
10	9.1a	7.8a	12.8b	14.2b
20	12.9a	18.4b	18.9b	23.8c
30	14.5a	20.0b	20.0b	23.9c
40	14.2a	20.3b	20.4b	25.5c
50	12.8a	15.9ab	17.9b	23.4c
60	10.0a	16.6b	19.2b	27.9c
70	10.0a	16.8b	17.7b	24.7c

Values with different letters between columns at the same depth are statistically different by Tukey´s test at the level 0.05.

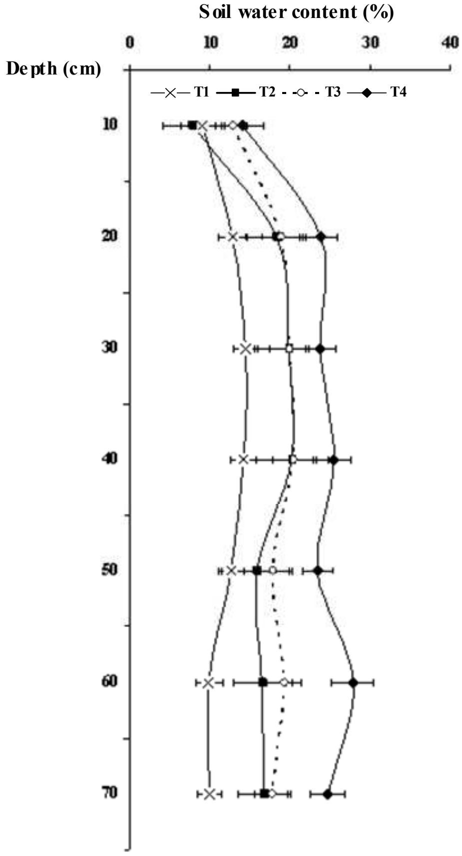

Figure 2. Soil water content at different depths. Each point represent the average of 80 readings. Horizontal bars are standard deviation.

Taking into account the whole irrigation season period, T4 had the higher water content than the remaining treatments (Fig. 3), followed by T3, T2 and T1. Also, θ_v was more regular in T4 and T1 than in T2 and T3, these latter two more were influenced by month time, since there was a decrease in T2 and T3 during August in both years.

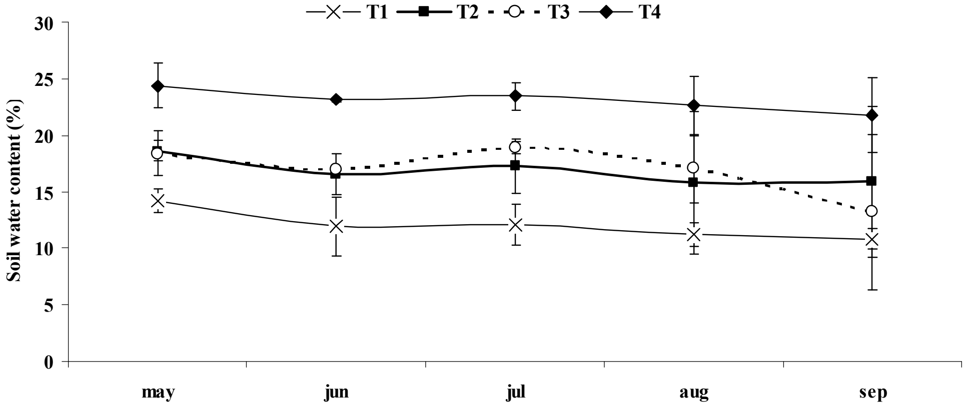

Figure 3. Average soil water content for each treatment during the irrigation period. Each point represents the average of 8 readings.

3.2. *Effect of the irrigation treatments and phenological stage on foliar nutrient concentrations*

3.2.1 Macronutriens

Table 4 presents the results for the analysis of variance for the response of macro- and micronutrients concentration to irrigation treatments at each phenological stage during the last two years of the experiment.

Respecting to nitrogen (N) there was not significant effect of the irrigation treatment in the average concentration of this element. However, N concentration changed significantly by the phenological stage, decreasing during flowering and post-harvest period (1.60 and 1.53%, respectively), agreeing with Ponchner et al. (1993). However, contrary to these authors, we obtained higher N-concentration during fruit set and fruit growth. At dormancy, we registered lower amount of N, which agrees with the results of Stassen and Janse van Vuuren (1997), and contrary to those obtained by Avilán (1971), with higher N concentrations in this period than in any other phenological stage.

Table 4. Foliar concentrations of macro- and micronutrients for irrigation treatments at each phenological stage

Irrigation treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})
T1	1.60a	0.16a	0.24a	2.48a	0.26ab	125a	23a	160ab	6a
T2	1.66a	0.14a	0.23a	2.28a	0.32b	141a	18a	118a	6a
T3	1.64a	0.21b	0.25a	2.59a	0.23a	134a	20a	191b	6a
T4	1.61a	0.17ab	0.24a	2.53a	0.25ab	125a	20a	145ab	6a
Phen. stage									
Dormancy	1.52a	0.17b	0.25ab	2.12a	0.20a	123b	14a	122a	5ab
Flowering	1.60a	0.28c	0.21a	2.48ab	0.25ab	62a	15a	171a	4a
Fruit set	1.74b	0.16b	0.23a	2.60b	0.34c	129b	21ab	162a	7bc
Fruit growth	1.74b	0.14ab	0.25ab	2.66b	0.32bc	173c	27b	159a	9c
Harvest	1.53a	0.10a	0.30b	2.51ab	0.22a	169bc	23ab	154a	7bc
Year									
1	1.64a	0.19a	0.26a	2.61a	0.25a	86a	19a	161a	6a
2	1.62a	0.14b	0.21b	2.33b	0.28a	177b	21a	146a	7a

Different letters within the same column are statistical different by Tukey´s test ($p < 0.05$); *, significant at $p < 0.05$; ns, not significant.

The flowering process lowered the N concentration, probably due to enzymatic activity and hormone synthesis that prompted the production of carbohydrates needs for cell division and elongation in the new spring shoots, to which nitrogenous compounds were directed from mature leaves (Leopold and Kriedemann, 1975; Guimaraes, 1982). In addition, Chowdhury (1971), Sen et al. (1972), Suryanarayana (1977) and Durán et al. (2005) have described lower foliar N values owing to flowering. The N-concentrations tended to recover during fruit set and fruit growth periods. Similar results for this period were obtained by Durán et al. (2005). In addition, high N concentrations have been related to excessive vegetative growth and less yields (Clarke and Clarke, 1987) with fruit physiological disorders (Guimaraes, 1982) and with other nutrient deficiencies (Ram et al., 1989). The N-concentration in this study ranged from 1.53 to 1.60%, which is considered adequate according to Young and Koo (1969) who established an interval of 1.0 to 1.5%. Regarding to phosphorous (P) concentration, irrigation treatment had significant effect ($p < 0.05$) being higher in T3 (0.21%) than in the remaining treatments (Table 4). Phenological stage also influenced significantly on P concentrations, being maximum for flowering. The flowering process experimented an increase in P concentrations respecting to the previous stage (dormancy) in contrast with the decline found by Guzmán et al. (1997) during these stages. Higher P concentrations during flowering may be related to the formation of nucleic acids, proteins and coenzymes, fundamental for respiration, photosynthesis and glycolysis during the reproductive process (Leopold and Kriedeman, 1975). P concentrations declined during fruit set and fruit growth stages, and similar results were obtained by Durán et al. (2005), being lowest in harvest. This was probably due to the function of P for the exportation of carbohydrates from leaves to fruits (Mengel and Kirkby, 1987). The concentration of P during the study period was within the recommended interval of 0.08 to 0.18 %, according to Reuter and Robinson (1986).

The K concentrations in leaves were not affected by irrigation treatments ($p > 0.05$) (Table 4). According to the phenological stage, K concentration in dormancy were higher that in the subsequent stages (flowering and fruit set), due to post-harvest recuperation, as was pointed out by Avilan et al. (1971). The decrease in K concentration during flowering agrees with the results found by Avilan (1971), Sergent et al. (1993) and Durán et al. (2005). K concentrations during fruit set and fruit growth remained relatively low, due to the K demand during fruit development and its traslocation from the leaves to the fruit through the phloem according to Mukherjee (1976) and Malo (1976). After harvest, K concentrations began to recuperate as was found by Durán et al. (2005), probably due to the lighter fruit load in this period. Finally, the K concentrations in this study ranged from 0.21 to 0.30 %; these values would be considered as low according to Wolfe et al. (1969) and Guimares et al. (1982), who establish an adequate interval of 1.0-1.2%.

The Ca concentrations did not differ significantly with the applied irrigation treatment; however, was found a decreasing trend in dormancy, as was also pointed out by Durán et al. (2005). By contrast, the Mg concentrations were significantly higher in T2 than in the rest of treatments ($p < 0.05$) and were lowest during dormancy and harvest period (0.20 and 0.22%, respectively). Both Ca and Mg concentrations increased again during fruit set and fruit growth periods, agreeing with Pathak and Pandey (1977) and Janse van Vuuren and Stassen (1997). In our experiment, the Ca concentrations were very similar to those obtained by Guzmán et al. (1997) for mango cv. Manila, with highest Ca concentrations after harvest and during fruit set. The lowest Ca-concentration during dormancy probably due to the reduction of transpiration during this period, since the relative humidity was higher, and consequently the reduction in translocation of Ca (Michael and Marschner, 1962).

3.2.2 Micronutrients

From the results of the present experiment, the Fe concentration was not affected significantly by irrigation treatment (Table 4). However, the Fe foliar concentration varied considerably for each phenological stage in all treatments. Fe concentration was significantly higher during fruit growth and harvest (173 and 169 mg kg^{-1}, respectively). Also, Fe concentration was were lowest during flowering period agreeing with those results obtained by Guzmán et al. (1997) and Durán et al. (2005). However, Fe concentrations for the present experiment were higher than 50 mg kg^{-1}, lower limit considered as deficient (Jones et al., 1991).

The Mn concentration was affected significantly by irrigation treatment, being highest in T3, followed by T1, T4 and T2 (191, 160, 145, and 118 mg kg^{-1}, respectively) (Table 3). By contrast, the effect of phenological stage was not significant. Although, there was a trend to be slightly higher during flowering, fruit set and fruit growth. Highest concentration of Mn was also found by Guzmán et al. (1997) for cv. Manila during flowering. This is due presumably to the translocation of Mn via floema to the meristemo tissues (Tiffin, 1972). Mutual interference was found between Fe and Mn, being the Fe concentration was minimum during flowering and fruit set, whereas in this period Mn concentrations were maximum. The tendency was also reported for other plant species (Roomizadeh and Karimian, 1996). Mn levels were in all treatments below the maximum recommended (250 mg kg^{-1}) (Jones et al., 1991). In addition, Ponchner et al. (1993) obtained Mn concentrations above this level.

The Zn and Cu concentrations were not affected by irrigation treatment and had both similar trends. Concentrations were lowest during dormancy and flowering and highest during fruit growth and harvest (Table 4). The Cu level fell at flowering (4 mg kg^{-1}), differing significantly ($p < 0.05$) from most of the phenological stages, and this decrease could be explained by the translocation from the mature leaves to the young ones (Loneragan, 1975) and towards the flowers, which are extremely dependent on this micronutrient for the normal pollen and ovary development (Mills and Benton, 1996). On the other hand, according to Guzmán et al. (1997), both Cu and Zn are concentrated in the seed during fruit growth, this favouring the fall in the levels of both elements in other organs, such as leaves during this period. The well-known antagonism between P and Zn was detected during all the study period, excepting for dormancy. Cu concentrations presented level below the recommended 10 mg kg^{-1} and Zn concentration was low (Jones et al., 1991), however, Zn levels were above 10 mg kg^{-1}, a level considered totally deficient (Mengel and Kirkby, 1987).

Thus, according to the results of the present work, the nutrient status was not affected by irrigation treatments at all with the exception of P, Mg and Mn.

3.2.3. Fruit nutrient concentrations of macro- and micronutrients

Table 5 shows the ANOVA analysis of concentrations of macro- and micronutrient for the different irrigation treatments and parts of the fruit. Differences among fruit components (skin, pulp, seed coat and sees) were statistically significant ($p < 0.05$) excepting for Cu, Fe, and Zn. There was a significant accumulation of nutrients in the seed for all the studied elements, excepting for Mn and Ca, which reached the highest concentration in skin. On the contrary, the lowest values for N, P, and K were found in the seed coat, whereas for Ca, Mg, Mn, and Fe in the pulp, and for Cu and Zn in the pulp and skin. However, differences were not statistically significant for Fe, Cu and Zn. The magnitude of the nutrient concentration of fruits in the present study agrees with Laborem et al. (1979) and Hiroce (1980), who registered greater N and K concentration, followed by Ca, Mg and finally P (Roy et al., 1971). Mg and Mn reached the highest concentrations in skin (0.23% and 32 mg kg^{-1}, respectively), agreeing with Guzmán et al. (1996). However, contrary to this author, the highest concentrations of K were found in seed, followed by skin and pulp. Seed was very rich in N, P, Cu and Zn concentrations (6.96%, 0.12%, 20 mg kg^{-1} and 34 mg kg^{-1}, respectively). Similar results in relation to seed and nutrient concentrations were found by Guzmán et al. (1996).

The effect of irrigation regimes on nutrient concentrations of fruits was statistically significant only for N, Cu, Fe and Zn (Table 5). However, was a tendency to reduce nutrient concentration in T4, excepting for Fe, Mn and Mg. This could be due to the effect of nutrient dilution. On the other hand, Wagner et al. (1985) found higher K and Ca concentration in pulp when irrigation was more abundant due to solubilization of these elements in soil, contrary to our results.

Table 5. Macro- and micronutrient concentrations by effect of irrigation treatments in different fruit parts of cv. Osteen.

Irrigation treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	Zn (mg kg^{-1})
T1	0.70b	0.06a	0.50a	0.18a	0.15a	21a	25a	76a	30ab
T2	0.58ab	0.06a	0.41a	0.18a	0.16a	26a	27a	88ab	36b
T3	0.53a	0.06a	0.49a	0.19a	0.14a	11b	22a	83ab	21a
T4	0.67ab	0.05a	0.45a	0.13a	0.16a	14b	27a	100b	25a
Fruit part									
Skin	0.61b	0.06b	0.47b	0.34b	0.23b	17a	32b	83a	25a
Pulp	0.50b	0.06b	0.51b	0.09a	0.09a	17a	20a	79a	25a
Seed coat	0.36a	0.02a	0.05a	0.13a	0.11a	19a	25a	102a	28a
Seed	0.96c	0.12c	0.83c	0.12a	0.19b	20a	24a	83a	34a
Year									
2007	0.75	0.07a	0.49a	0.20a	0.16a	25a	28a	96a	29a
2008	0.47b	0.06b	0.43a	0.14b	0.15a	11b	23b	77b	27a
ANOVA									
Fruit part	*	*	*	*	*	ns	*	*	ns
IT	*	*	ns	*	ns	*	*	*	ns
Year	*	ns	ns	ns	ns	*	ns	*	*
Interaction									
FP x Year	ns	*	ns	ns	ns	ns	*	ns	ns
FP x IT	ns	*	ns	ns	ns	*	*	*	ns
Year x IT	ns	*	ns	ns	ns	*	ns	ns	*
FP x Year x IT	ns	ns	ns	ns	ns	ns	ns	ns	ns

FP, Fruit Part; IT, Irrigation Treatment. Different letters within the same column are statistical different by Tukey´s test ($p < 0.05$); *, significant at $p < 0.05$; ns, not significant

3.2.4. Fruit quality

Average fruit length and width for the studied treatments and for the two last years is shown in Table 1. The T4 obtained the highest fruit length and width values (14.1 and 9.5 cm, respectively), differing significantly from the remaining treatments, which is in concordance with the fruit weight. On the contrary, the T1 produced the lowest fruits (13.1 and 8.6 cm, respectively).

Table 6. Characteristics of mango fruits during two growing seasons (2007-2008) for each treatment

	2007					2008				
Irrigation treatment	Skin (%)	Seed (%)	Pulp (%)	TSS (ºBrix)	Titratable acidity	Skin (%)	Seed (%)	Pulp (%)	TSS (ºBrix)	Titratable acidity
T1	10.1a	4.2a	85.7a	18.81a	0.45a	8.2a	5.7a	86.1a	17.8a	0.21a
	(± 0.7)	(± 0.7)	(± 1.2)	(± 0.5)	(± 0.2)	(± 1.6)	(± 1.5)	(± 1.5)	(± 1.3)	(± 0.1)
T2	10.3a	4.3a	85.4a	17.56ab	0.32a	8.3a	4.7a	87.1a	17.3a	0.25a
	(± 1.4)	(± 0.5)	(± 1.0)	(± 0.4)	(± 0.1)	(± 1.8)	(± 1.0)	(± 2.8)	(± 1.7)	(± 0.0)
T3	9.3a	4.4a	86.3a	16.58ab	0.46a	7.5a	5.6a	86.9a	17.0a	0.21a
	(± 1.0)	(± 0.6)	(± 0.8)	(± 1.3)	(± 0.2)	(± 0.9)	(± 0.6)	(± 0.9)	(± 1.3)	(± 0.1)
T4	11.3a	4.0a	84.7a	15.42b	0.44a	6.9a	4.6a	88.5a	16.6a	0.21a
	(± 1.6)	(± 0.5)	(± 1.5)	(± 0.8)	(± 0.1)	(± 1.2)	(± 0.5)	(± 0.8)	(± 0.7)	(± 0.0)

TSS, Total Soluble Solids; Different letters within the same column are statistical different by Tukey´s test ($p < 0.05$); ± standard deviation

Table 6 shows the weight percentage for skin, pulp and seed for studied treatments and for the last two seasons (2007 and 2008). The skin weight percentage ranged from 9.3 to 11.3% and from 6.9 to 8.2% for 2007 and 2008, respectively. However, skin weight had no significant differences between treatments, and our results were slightly lower than those obtained by Laborem et al. (1979) for cv. Manzana, Gleen and Zill (10.2-17.9%) and those obtained by Singh (1960) with cv. Filipinas (11-18%). In relation to the pulp weight percentage ranged from 84.7 to 86.3% and from 86.1 to 88.5%, for 2007 and 2008, respectively. Our pulp weight percentage values for cv. Osteen were higher than those obtained by Laborem et al. (1979) with cv. Manzana, Gleen and Zill (67.3-77.9%). By taking into account the two years, we obtained differences for pulp: seed ratio, having the following pattern: T4 > T2 = T3 > T1 (22.5, 19.9, 18.4, and 16.8, respectively) ($p < 0.05$). In general, differences in percentage in weight of skin, pulp and seed were not affected by irrigation treatment, since it is normally more related to the variety of mango itself rather than in any other factors. In 2007, differences in total soluble solids (TSS) were statistically significant ($p < 0.05$), being highest in T1, indicating a possible active sugar accumulation due to the lower amount of irrigation. These results have also been found in other types of crops (González, 1998). Also, this trend T1 > T2 > T3 > T4 in TSS was recorded in 2008, however, differences were not significant. In addition, during 2008, skin weight percentage was slightly higher in T1 and T2 than in T3 and T4. The titratable acidity was not affected significantly by irrigation treatment. The water percentage for the different part of the fruit differed statistically ($p < 0.05$): seed > skin = seed > pulp (45, 60, 65, and 78%, respectively). These results were very similar to those obtained by Guzmán et al. (1996) for mango cv. Manila (64, 80 and 58%, for skin, pulp, and seed respectively). On the other hand, differences for fruit dry matter were not affected by irrigation treatment, contrary to the results found by Diczbalis et al. (1993), who obtained increase in dry matter as irrigation amount was decreased. Also, Baker (1992) pointed out an increase of dry matter during late fruit maturity by removing irrigation.

4. Conclusion

In this study, our results support that the effect of irrigation amount on mango are significantly important in order to improve the water saving strategies for sustainable subtropical agriculture in orchard terraces. The results indicated that T2 reached the highest yield and WUE, therefore, increasing water amount did not implicate higher yield. Also, yield was highly correlated with the number of fruits and not with fruit size. Average fruit size was higher for T3 and T4, being length and width were significantly higher, however, T2 obtained reasonable marketable fruit size. Significant second degree polinomial relationships between mango fruit yield and irrigation were found. On the other hand, the nutrient status of mango tree was not affected by irrigation treatment, excepting for P, Mg and Mn. In addition, there were not found relationship between fruit yield and nutrient concentration.

Thus, according to the results of the present experiment, the T2 (50% ETc) should be adopted as a most appropriate irrigation strategy for achieving sustainable water management in mango orchards under Mediterranean subtropical climate.

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CONCLUSIONES GENERALES

1. En la cuenca estudiada durante el periodo de 29 años, la principal fuerza que ha impulsado a los cambios en el uso del suelo han sido la agricultura intensiva de regadío en terrazas basada en cultivos subtropicales económicamente más rentables. Los cultivos tradicionales de secano consistentes en almendro y olivo han sido sustituidos o abandonados en su mayor parte.

2. La erosión crónica de los suelos de los taludes de las terrazas construidas con cultivos subtropicales ha promovido los problemas de degradación física, química y biológica de los suelos, comprometiendo seriamente la estabilidad de la estructura y sugiriendo la urgente necesidad de la aplicación de medidas correctoras para su control.

3. La implantación de plantas aromáticas consistentes en tomillo (*Thymus mastichina*) y lavanda (*Lavandula dentata*) y de vegetación nativa espontánea en los taludes de las terrazas reducen sustancialmente las tasas de erosión y escorrentía, así como las pérdidas de nutrientes, al tiempo que incrementa el contenido en carbono orgánico, y por lo tanto la calidad de los suelos. Asimismo, cabe destacar que las cubiertas de plantas aromático-medicinales además de proporcionar beneficios medioambientales puede ofrecer la posibilidad de beneficios económicos a los agricultores en contraste a la vegetación nativa.

4. El ecosistema agrícola (alterado) formado por cultivos subtropicales en terrazas tuvo menores tasas de descomposición de su hojarasca que el sistema no alterado (laderas sin terrazas, ni cultivos y cubiertos de vegetación nativa espontánea). Este desequilibrio en el sistema alterado se vio compensado con la implantación de plantas aromático-medicinales en los taludes de las terrazas, que tuvieron altas tasas de descomposición de su hojarasca. Por otro lado, se ha demostrado que las hojas del chirimoyo pueden contribuir a una mayor tasa de incorporación de nitrógeno al suelo, mientras que las de mango y aguacate pueden servir para un aporte de nitrógeno a largo plazo. En consecuencia, la implantación de las cubiertas en los taludes de terrazas puede promover a mejorar y mantener la calidad de los suelos y mitigar el impacto negativo de la agricultura intensiva de regadío, consolidándose como una estrategia sostenible en la conservación del recurso suelo.

5. La aplicación tradicional de fertilizantes en el área de estudio es excesiva, es decir, por encima de las necesidades reales del cultivo. Esto conlleva un alto riesgo potencial de contaminación de aguas subterráneas sobretodo de pozos localizados en cotas inferiores. El

balance de nutrientes realizado sugiere la aplicación de correcciones en los planes de fertilización de estos cultivos con la finalidad de optimizar su empleo y promover medidas para minimizar el efecto de las actividades agrícolas.

6. El empleo tradicional de cantidades importantes de agua de riego no incrementa la producción de frutos de mango en terrazas de cultivo, una medida correctora de las dosis de riego mediante el uso del coeficiente de cultivo (Kc) determinado en el presente trabajo en condiciones subtropicales del sudeste peninsular español será una herramienta muy útil para la aplicación de estrategias sostenibles en el uso del recurso agua.

GENERAL CONCLUSIONS

1. In the watershed studied for 29 years, the main driving force in land-use changes has been intensive irrigation on terraces planted with subtropical crops, which are economically more profitable. Most of the rainfed crops consisting of almond and olive have been replaced or abandoned.

2. The permanent soil erosion on the taluses of terraces with subtropical crops has promoted chemical, mechanical, and biological soil degradation, endangering the stability of these structures. Therefore, it is urgent to establish protective measures for their control.

3. The installation of aromatic plants consisting of thyme (*Thymus mastichina*) and lavender (*Lavandula dentata*), and also the spontaneous native vegetation growing on the terraces significantly reduces runoff, erosion rates, organic carbon and nutrient losses. At the same time it promotes soil organic carbon and therefore soil quality. In this sense, aromatic-medicinal plant covers could also constitute major economic income for local farmers, contrary to spontaneous vegetation.

4. The altered agricultural ecosystem, with subtropical crops on terraces had lower litter decomposition rates than the non-altered ecosystem (slopes without terraces and with natural spontaneous vegetation). This imbalance was offset by the installation of aromatic-medicinal plant covers, which had higher litter decomposition rates. Furthermore, it has been demonstrated that fallen cherimoya leaves can contribute to faster nitrogen-recycling and thus higher soil-nitrogen accumulation. However, mango and avocado litter could contribute to long-term nitrogen accumulation. Thus, the planting of aromatic plant covers on the taluses of terraces can improve and maintain soil quality as well as mitigate the negative impact of intensive irrigated agriculture, constituting a sustainable measure for soil conservation.

5. The fertilizers in the study area are applied over the plant requirements. This implies a high risk of groundwater pollution, mainly in wells located at lower levels. The nutrient balance studied indicates that the planning of fertilizer application must be corrected to optimise their efficiency and it is necessary to promote measures to minimize the effects of agricultural activities.
6. The traditional use of high irrigation rates does not mean higher yield of mango on orchard terraces. The calculated crop coefficient (Kc) in this work for subtropical

conditions in southern Spain, can be used to correct irrigation rates and will be a very useful strategy for sustainable agriculture in water saving.

ANEXO

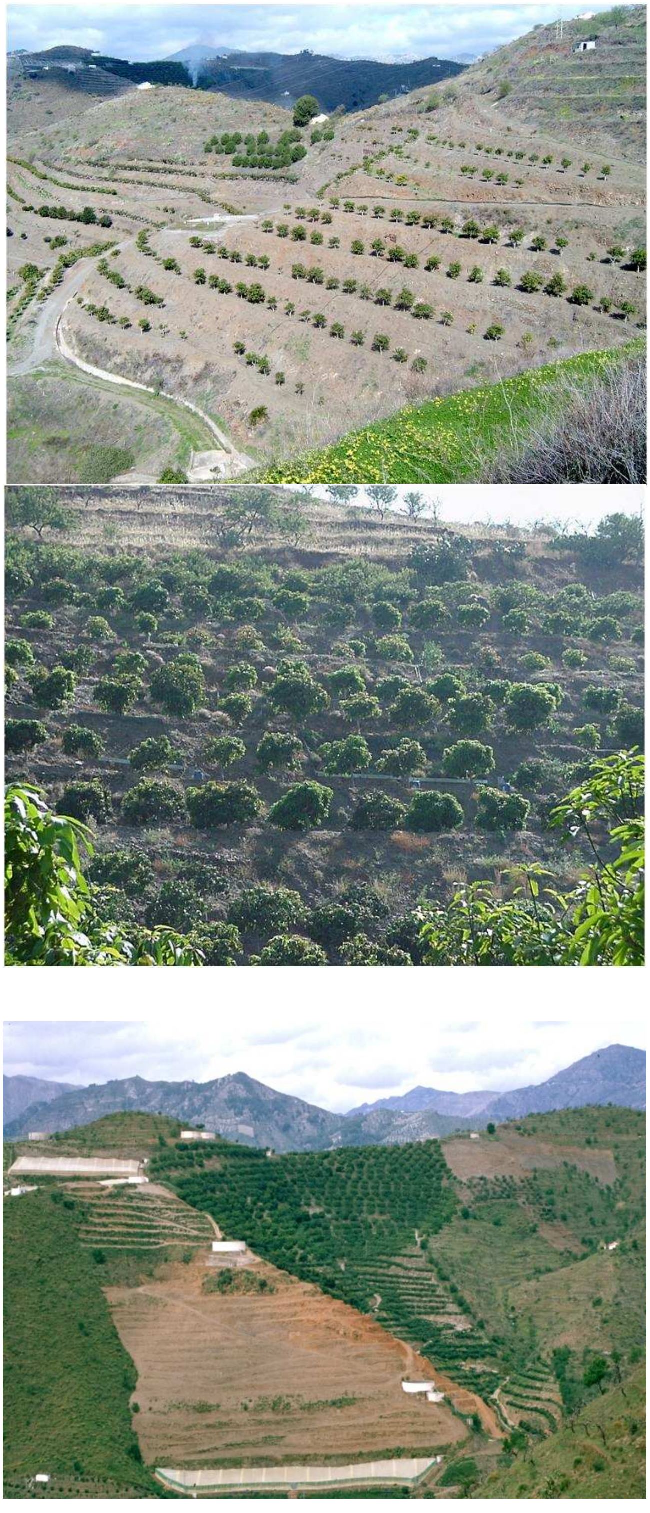

Foto 1. Cultivos tropicales y subtropicales en terrazas. Construcción de terrazas.

Foto 2. Parcelas de erosión en los taludes de las terrazas con cultivos tropicales y subtropicales. Cárcavas producidas en la terraza tras un evento muy erosivo

Foto 3. Bolsas de nylon con hojas de cultivos tropicales y subtropicales para ensayos de descomposición de hojarasca

Foto 4. Lisímetro de drenaje en chirimoyo

Foto 5. Ensayos de riego en mango y chirimoyo. Sonda FDR para medir humedad en suelo

Curriculum Vitae

Carmen Rocío Rodríguez Pleguezuelo es Licenciada en Ciencias Ambientales por la Universidad de Granada (España). Tras finalizar sus estudios, obtuvo una beca de tecnólogo del Instituto Andaluz de Investigación y Formación Agraria, Pesquera y de la Producción Ecológica por Resolución de 2 de Enero de 2004 (publicado en el BOJA núm. 48 de 10 de Marzo de 2004 titulada “Relaciones suelo-agua-planta en olivar” (2004-2005). Tras el disfrute de ésta, obtuvo una beca predoctoral de formación de personal investigador con título “Impacto medioambiental del cultivo de especies subtropicales en terrenos con fuertes pendientes. Medidas integradas para el cultivo sostenible” por Resolución de 31 de Octubre de 2005 del Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA). Durante este periodo ha realizado una estancia de 7 meses en Purdue University, Agronomy Department and National Soil Erosion Research Laboratory (West Lafayette, Indiana, USA). Es miembro del grupo AGR-144 del IFAPA. Sus líneas de investigación son estudios concernientes al manejo y conservación de suelos y aguas a nivel de laderas y terrazas, optimización del uso del agua de riego, ha trabajando con distintos climas (árido, semiárido y mediterráneo subtropical) y cultivos (plantas aromáticas, olivar, almendro y subtropicales). Ha participado en 3 proyectos de investigación. Su producción científica con 14 (+ 4 en revisión) artículos, 11 en revistas internacionales reconocidas en el SCI (*Agriculture, Ecosystems & Environment, Pedosphere, Agronomy for Sustainable Development, Fruits* y *Catena)*, 3 en revistas no SCI (*European Journal of Plant Science & Biotechnology*, *The Environmentalist, The Open Agriculture Journal*) y 3 en revistas nacionales (*Edafología, Ecosistemas* y *Agricultura*). Ha editado 3 libros y 2 capítulos de libro. Cuenta con 16 contribuciones a congresos 11 internacionales y 5 nacionales. Ha tenido actividad docente con universidades españolas (Granada y Jaén), europeas (Wageningen University and Vriej Universiteit van Amsterdam) y norteamericanas (Purdue University) y otros organismos nacionales (Patronato de Cultivos Subtropicales de Almuñécar). Actualmente ejerce su labor investigadora en el IFAPA Centro Camino de Purchil, Granada. Su dirección de correo electrónico es *crocio.rodriguez@juntadeandalucia.es.*

Curriculum Vitae

Carmen Rocío Rodríguez Pleguezuelo earned her "Environmental Sciences Degree" at the University of Granada (Spain). Afterwards, she was awarded a fellowship from the Agricultural and Ecological Production Andalusian Research and Transfer Institute entitled "Plant-Water-Soil relationship in olive tree" (2004-2005). After this period, she was awarded a doctoral grant for researchers' education entitled "Environmental impact of subtropical crops on steel sloping terrain along the coast of Granada. Towards sustainable agriculture" from the National Research and Agricultural Technology Institute INIA. During this period, she also spent seven months at Purdue University, Agronomy Department and National Soil Erosion Research Laboratory (West Lafayette, Indiana, USA). She is a member of AGR-144 research group at IFAPA Centro Camino de Purchil, Granada (Spain). She is carrying out research related to soil and water conservation on slopes and terraces, irrigation efficiency in different climates (arid, semiarid and subtropical), and crops (aromatic plants, olive, almond and subtropical crops). She has participated on 3 research projects. She has published 14 scientific papers (+ 4 in revision), 11 in international journals from SCI (*Soil & Tillage Research, Agriculture, Ecosystems & Environment, Pedosphere, Agronomy for Sustainable Development, Fruits,* and *Catena*), 3 in non-SCI journals (*European Journal of Plant Science & Biotechnology, The Environmentalist,* and *The Open Agriculture Journal*) and 3 in Spanish national journals (*Edafologia, Ecosistemas,* and *Agricultura*). In addition, she has edited 4 books and 2 chapters of books. Also, she has participated in 16 congresses (11 international and 5 national). Simultaneously, she has been a teacher assistant at different universities in Spain (Granada and Jaén), Europe (Wageningen University and Vriej Universiteit van Amsterdam), and USA (Purdue University) and has also worked at other types of national research organizations (Patronato de Cultivos Subtropicales de Almuñécar, Granada, Spain). At the present, she works at the Andalusian Research Institute for Agricultural and Ecological Production (IFAPA) at Centro Camino de Purchil, Granada, Spain. She can be contacted at *crocio.rodriguez@juntadeandalucia.es.*