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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A R T I C L E   I N F O

A B S T R A C T

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, *O. europaea* and *G. umbellata* were the slowest in decomposing (1.18 and 1.01 years^{-1}, respectively) contrary to *L. officinalis*, which decomposed fastest (2.22 years^{-1}). Only *L. officinalis* and *P. purpurea* registered a net N-release at the end of the study. The AMMPs showed different decomposition patterns: *L. dentata* registered the highest decomposition rates and *Rosmarinus* the lowest (1.9 and 1.1 years^{-1}, respectively). *T. mastichina*, *L. dentata*, and *S. 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.

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

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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, 2000; Tecklay 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 (Musvoto 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 receives 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; Rodríguez et al., submitted for publication). 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) (36°48′00″N, 3°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 (Elías and Ruiz, 1977). The average annual rainfall in the study zone is 449.0 mm with a mean annual temperature of 20.8 °C. 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.
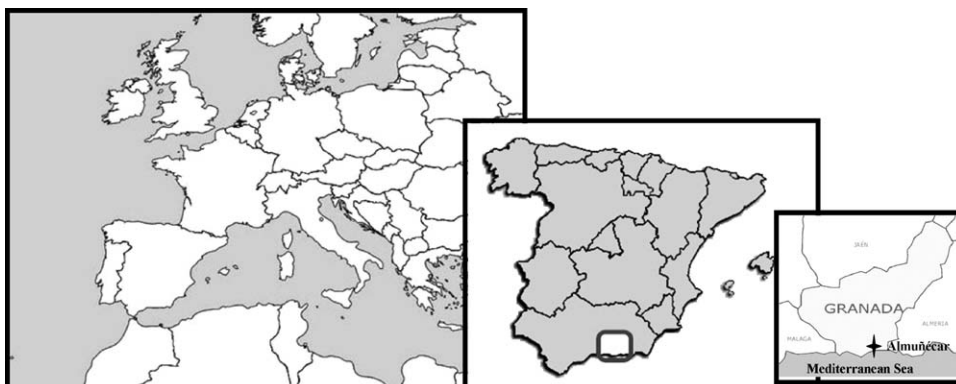

Fig. 1. Location of the study area in south-eastern Spain (Almuñécar, Granada).

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 m², 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 × 15 cm × 1 mm mesh for the AMMPs and natural spontaneous shrubs, and 50 cm × 25 cm × 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., submitted for publication) included: *T. mastichina* L., *L. dentata* L., *Satureja ovovata* Lag., *A. cytisoides* L., and *R. officinalis* L. cv *postratum*. The local subtropical crop leaves were from orchards of: a 15-year-old avocado (*P. americana* Mill.), 16-year-old mango (*M. indica* L.), 17-year-old cherimoya (*A. cherimola* Mill.), and 12-year-old loquat (*E. 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 × 50 cm quadrat. The most representative natural spontaneous shrubs consisted of *R. sphaerocarpa* L., *L. officinalis* Chaix, *G. umbellata* L'her, *O. europaea* cv. *sylvestris*, and *P. 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 70 °C to constant weight and weighed for the determination of remaining biomass. The loss of mass over time was expressed with the exponential decay model:

$$W_t = W_o e^{-kt} \tag{1}$$

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 (year^{-1}) (Olson, 1963):

$$k = -\ln(W_t/W_o) \tag{2}$$

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

$$R_t = \frac{1}{k} \tag{3}$$

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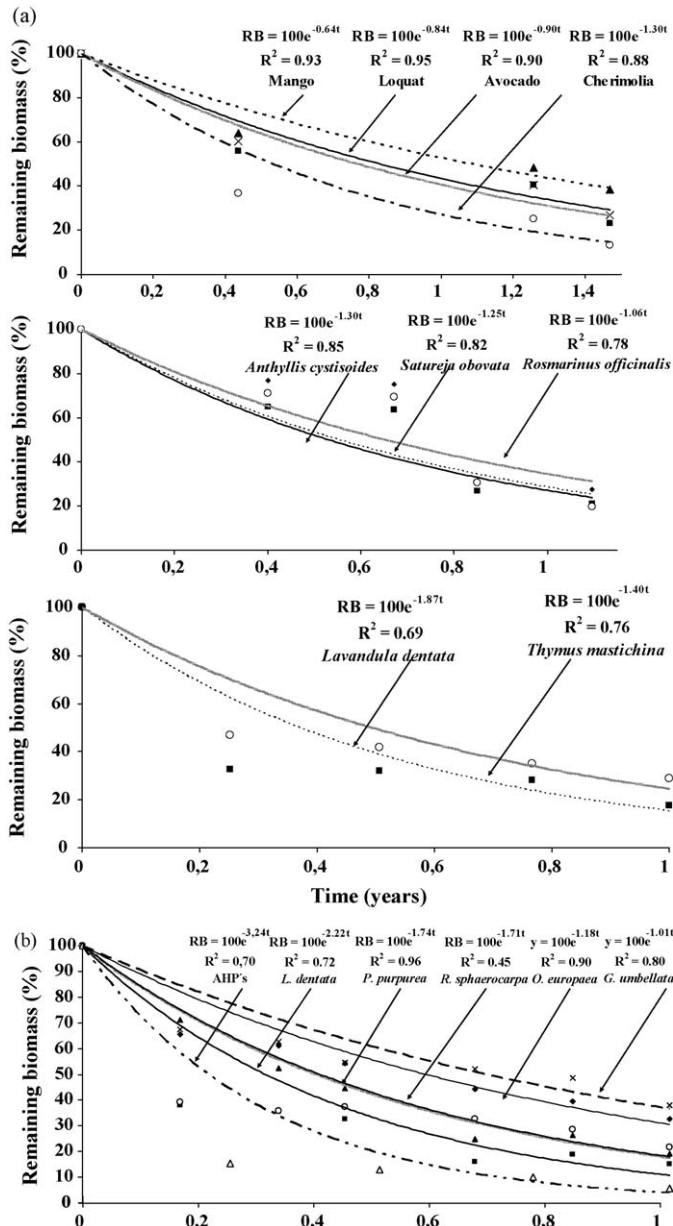
3.1.1. Subtropical crop leaf decomposition: mango, cherimoya, loquat and avocado

Mass-loss dynamics over the study period were best described by the single exponential decay model (Fig. 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

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*.

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).

biomass at T_f (the last retrieval, $t = 526$ days) was regressed against the initial C:N ratio (Fig. 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

Fig. 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). Percentage of remaining biomass (dry weight) in the leaf litters studied in the UES during the decomposition process (b). AHPs, Annual herbaceous plants mixture.

days. On the other hand, Musvoto 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. 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
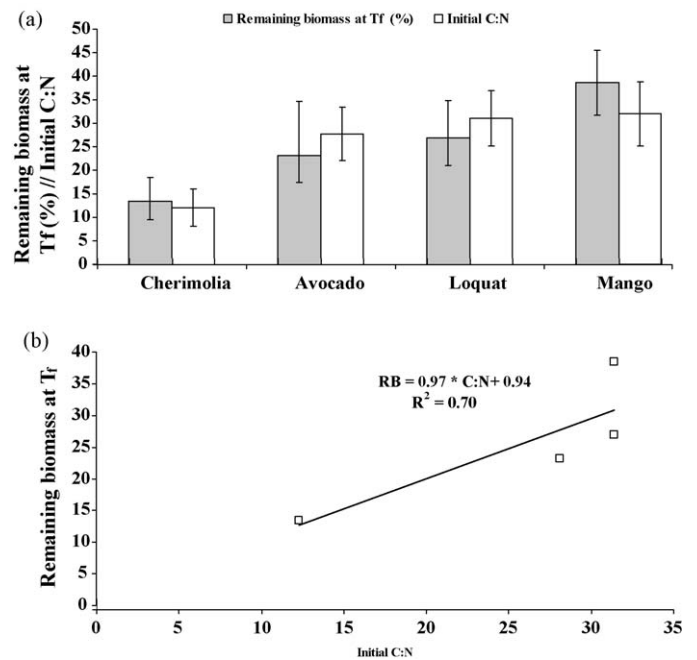

Fig. 3. Relationship between the initial C:N ratio and remaining biomass (RB) at T_f (536 days) for the subtropical crops studied. Vertical bars mean standard deviation ($n = 8$) (a). Linear regression between initial C:N ratio and remaining biomass at T_f (b).
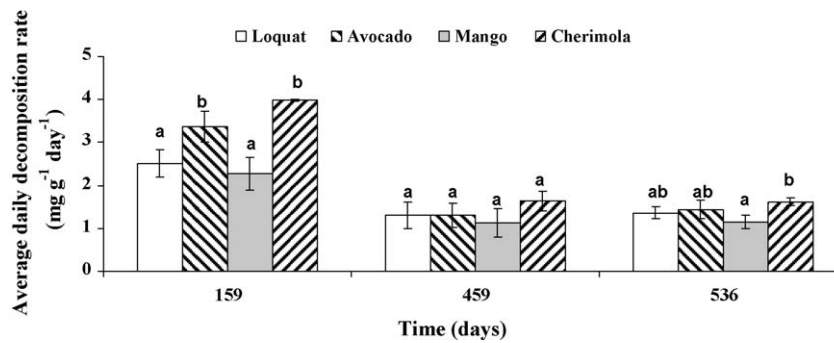
Fig. 4. Average daily decomposition rate of subtropical leaves during the study period. Bars show standard deviation (n = 8). Different letters with the same day-group mean significant differences among plants (Tukey test, $p < 0.05$).

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.

Average daily decomposition rates of leaf litter in the four studied subtropical crops are shown in Fig. 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. 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 *T. mastichina*, *R. officinalis*, *A. cytisoides*, *S. obovata*, and *L. dentata* were 1.40, 1.06, 1.30, 1.25, and 1.87 years^{-1}, respectively (Fig. 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$_f$ = 0.30C:N + 12.3, R^2 = 0.96, $p < 0.05$) (Fig. 5a), and this relationship was inverse with the initial N content (%) and RB$_f$ (RB$_f$ = −7.28N + 33.0, R^2 = 0.86) (Fig. 5b). These relationships were not statistically significant when *T. 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 Staaf, 1981; Palm and Sanchez, 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 with *L. officinalis*, *P. purpurea*, *R. Sphaerocarpa*, *O. europaea*, and *G. umbellata*, we found decomposition rates of 1.06, 1.74, 1.71, 1.18 and 1.01 years^{-1}, respectively (Table 2, Fig. 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
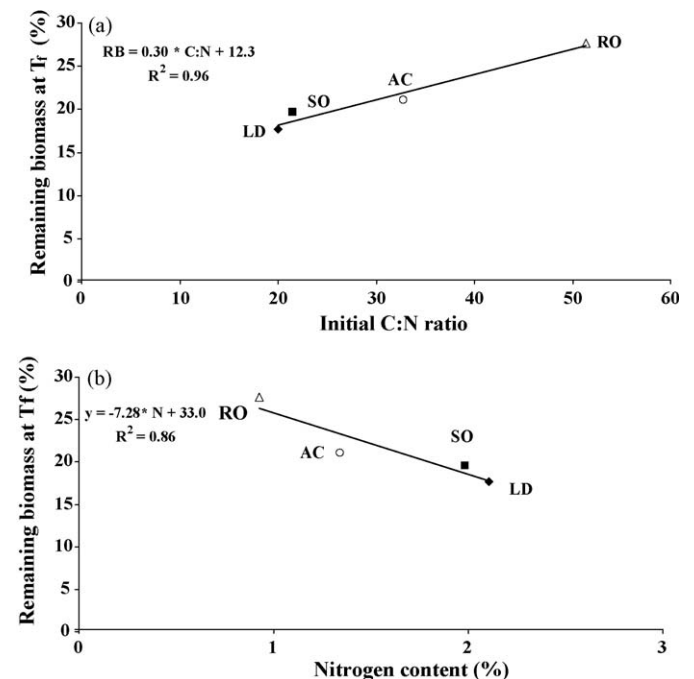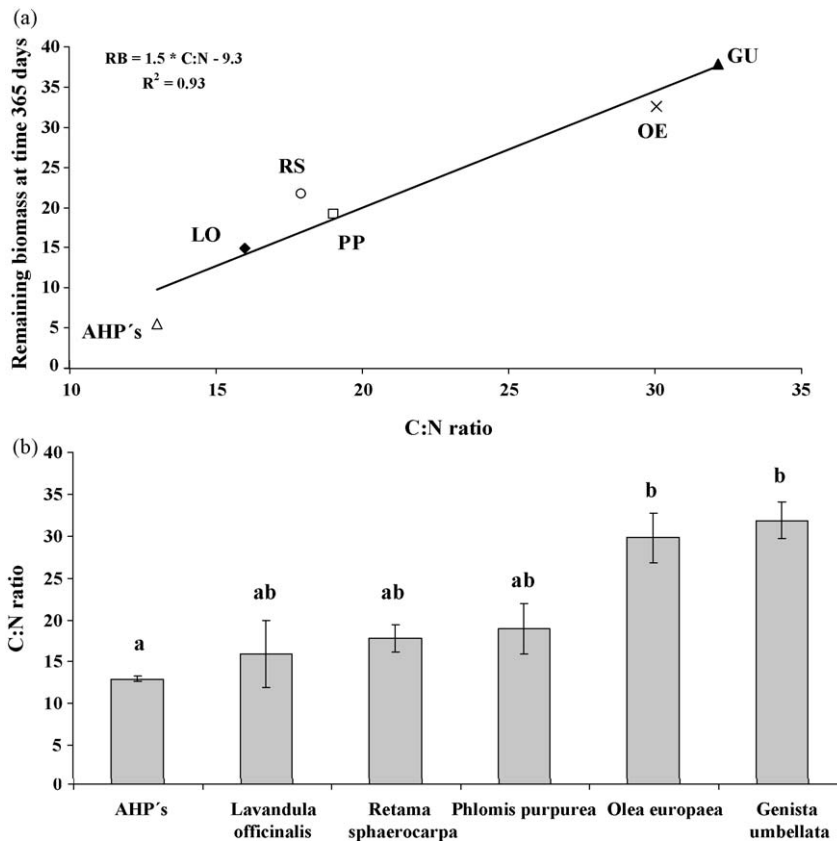

Fig. 5. Linear relationship between remaining biomass (RB) at the end of the experiment (T_f) and initial C:N ratio in the litter (a). Linear relationship between remaining biomass at the end of the experiment (T_f) and initial N content in litter. LD, *Lavandula dentata*; AC, *Anthyllis cytisoides*;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

Fig. 6. Relationship between the initial C:N ratio and remaining biomass at T_f (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 ($n = 6$).

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., submitted for publication). 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 2 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 ($R^2 = 0.93$, $p < 0.01$; Fig. 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 (Fig. 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. 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 ($RB_f = 42.2 - 11.5N$; $p < 0.05$). 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). Fig. 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 (Fig. 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 Hawaguchi, 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
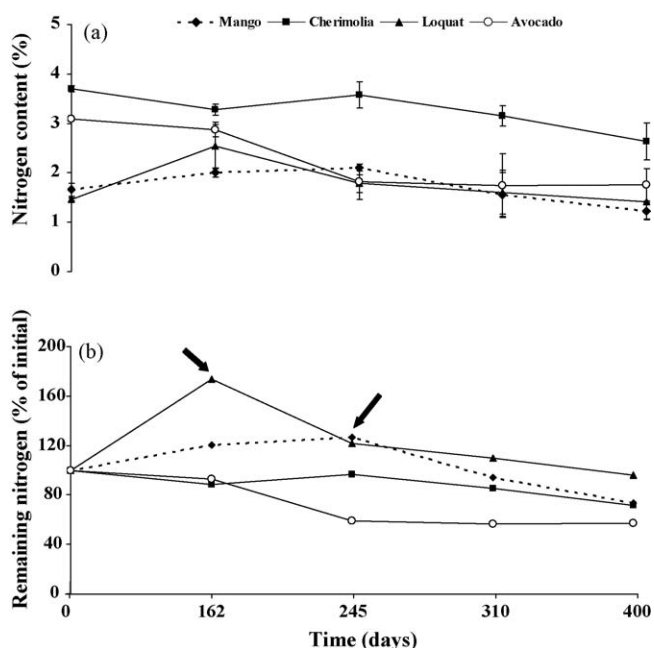
Fig. 8. Carbon–content evolution over time for the subtropical crops. Vertical bars represent standard deviation ($n = 8$).

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

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).

highest amount of N immobilized (Fig. 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 (Fig. 7a and 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 4 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). 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, Musvoto 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., 1982).

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 (Fig. 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 *L. dentata*, *T. mastichina*, and *S. obovata*. Moreover, a net mineralization occurred from the beginning of the experiment for *T. mastichina*, and *L. dentata*. However, N concentration increased in *R. officinalis* and *A. cytisoides* (Fig. 9).
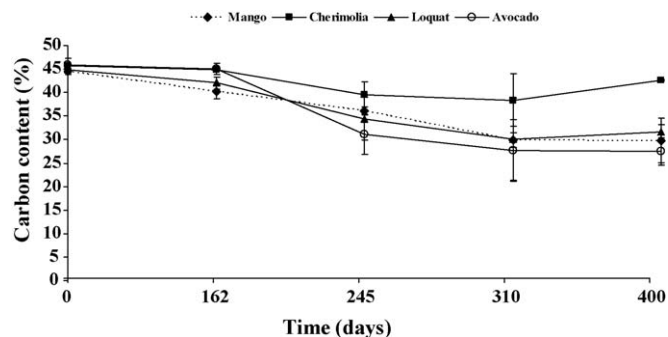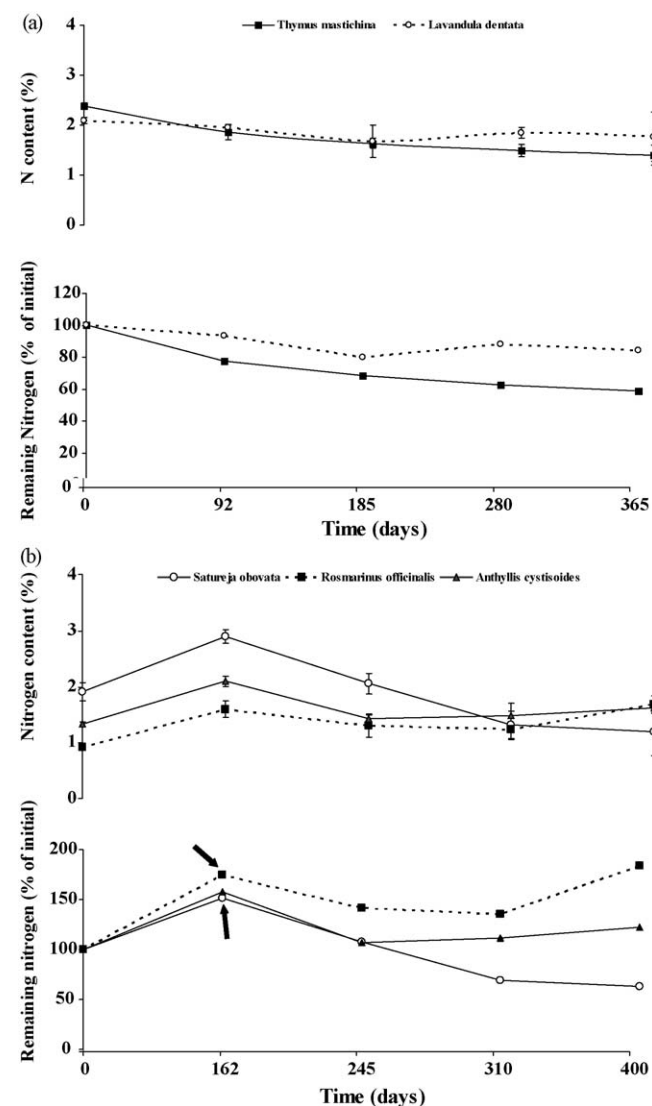

Fig. 9. Changes in N content (a) and remaining N (% of initial values) during the decomposition period in the five aromatic and medicinal plants (b). Vertical bars represent standard deviations ($n = 6$ for *Thymus mastichina* and *Lavandula dentata*; $n = 8$ for *Satureja obovata*, *Anthyllis cytisoides* and *Rosmarinus officinalis*). Arrows indicate the retaining period in *Rosmarinus officinalis*, *Satureja obovata*, and *Anthyllis cytisoides*.
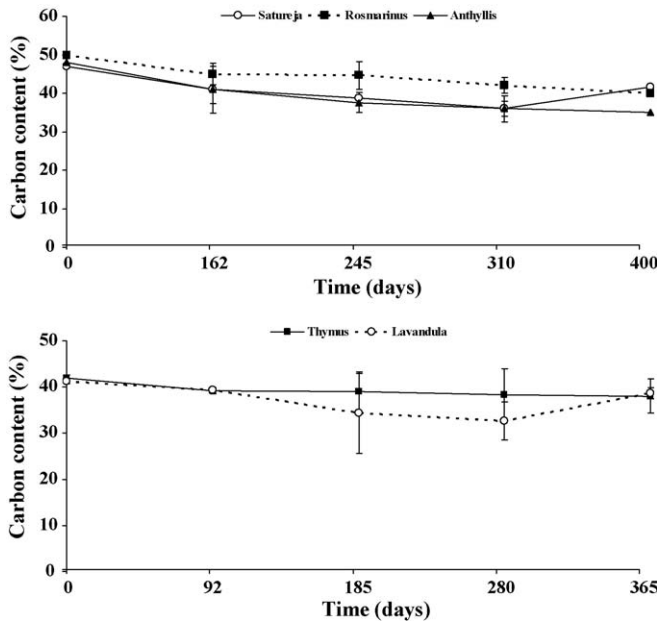
Fig. 10. Carbon content evolution in aromatic and medicinal plants. Vertical bars represent standard deviations ($n = 6$ for *Thymus mastichina* and *Lavandula dentata*; $n = 8$ for *Satureja obovata*, *Anthyllis cytisoides* and *Rosmarinus officinalis*).

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

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. 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 (Fig. 10). 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.

3.4. 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 (Fig. 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; Fig. 11b). On the contrary, *Lavandula* and *Phlomis* litter, decreased their N contents to 56 and 83% of the initial values, respectively (Fig. 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 2 months. By contrast, for AHPs, 90% of the N remained after 3 months. We found no net release in the
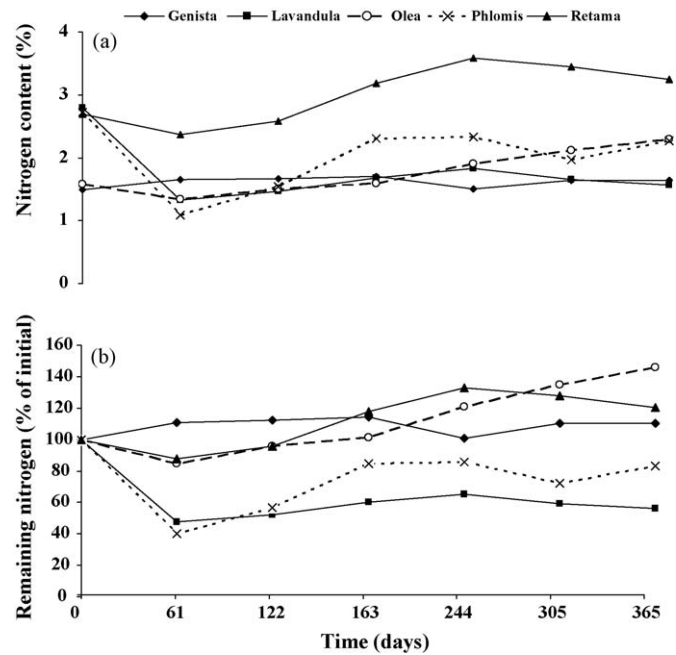
rest of plants, but rather the opposite—net immobilization. However, Oliver et al. (2002) recorded 2.4% of the N content in *Retama* as not immobilized nor released, as the concentration after one year of experiment remained approximately the same. *Retama* and *Genista* are common legumes in semiarid 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). 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 $T_f = -6.4 + 1.3$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 *O. europaea* and *G. 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

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

Table 4

Q9 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

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

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 agroecosystems 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 *T. mastichina* (3.18), *L. dentata* (1.12), *L. officinalis* (7.26), or *P. purpurea* (4.83).

4. Conclusion

This work demonstrates the importance of litter decomposition and nutrient dynamics in this particular agroecosystem of southeastern 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, *L. dentata* decomposed very quickly and released N from the beginning; on the contrary, *R. officinalis*, *S. obovata* and *A. cytisoides* immobilized N during the first 5 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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