# Fertilizer recommendations for olive based upon nutrients removed in crop and pruning

M. Ângelo Rodrigues [a,*], Isabel Q. Ferreira [b,1], Ana Marília Claro [a,1], Margarida Arrobas [a,2]

[a] *Mountain Research Centre – Polytechnic Institute of Bragança, Campus de Santa Apolónia, Ap. 1152, 5301-855 Bragança, Portugal*
[b] *Polytechnic Institute of Bragança, Campus de Santa Apolónia, Ap. 1152, 5301-855 Bragança, Portugal*

A B S T R A C T

The above-ground part of fourteen, young (ten-year-old), rainfed olive trees were separated into trunk (wood and bark), main branches (wood and bark), secondary branches (wood and bark), twigs, leaves and fruits. Based on the dry matter and nutrient concentration in the different tissues, the total amounts of nutrients in each tree were estimated. A controlled scheme of pruning conducted annually allowed the quantification of the amount of nutrients removed in pruning. Olive yields and nutrient concentrations in the fruits (pulp and pit) were used to quantify the nutrients removed in the crop. The results showed that the amounts of nutrients annually removed were relatively low, suggesting that more conservative fertilizer applications could be made than those usually recommended by the laboratories of soil testing and plant analysis. In this orchard, with a yield goal of 2500 kg fruit $ha^{-1}$, the nitrogen (N) rate to apply as fertilizer should not exceed 20 kg N $ha^{-1}$ $year^{-1}$. The transient nature of N in the soil/plant systems recommends that N be applied every year to increase the nutrient-use efficiency. The application of other nutrients as fertilizer should be diagnosed beforehand by soil testing and/or plant analysis. Nutrients removed by crop and pruning do not provide all the information on the need for supplemental fertilizer applications. Soil testing and plant analysis should be used routinely for a continuous adjustment of the fertilizer program.

*Keywords:*
*Olea europaea* Nutrients removed by pruning Nutrients removed by crop Fertilizer recommendation Nitrogen fertilization

## 1. Introduction

The literature on olive nutrition and fertilization has been relatively abundant. A comprehensive review of the field studies carried out in the middle of the 20th century on olive nutrition and fertilization was provided by Hartmann et al. (1966). Those early surveys stressed that olive markedly responded to nitrogen (N) fertilization in soils of low fertility. Olives grown in more fertile soils showed much less response to N applications. Potassium (K) has also been reported as an important nutrient in olive. In orchards grown under K-deficient soils, fertilized trees showed increased growth and yields, in comparison to unfertilized trees. The importance of boron (B) in olive nutrition was also emphasized from those early studies. Boron deficiency was recorded as a worldwide nutritional disorder whose symptoms may be alleviated through boron application as a fertilizer. Regarding phosphorus (P), it seems that there have been no cases of P deficiency, with trees responding to P applications, reported from field-grown olive trees (Hartmann et al., 1966).

The high importance of N in olive fertilization has been confirmed in more recent studies. Rodrigues et al. (2011) reported a significant and progressive decrease in olive yield when N was eliminated from the fertilization plan for four years, in comparison with treatments where N was applied annually. Jasrotia et al. (1999) also found a significant increment in olive productivity with increasing N fertilizer rates. Several studies have continued to report the importance of B fertilization as a means of increasing olive productivity (Larbi et al., 2011; Soyergin, 2010). Other studies demonstrated the importance of boron nutrition in flower quality and fruit set (Perica et al., 2002) or the existence of a close relationship between the B nutritional status of trees and olive yield (Arrobas et al., 2010). Sarrwy et al. (2010) reported a remarkable improvement in leaf mineral status, yield and fruit quality after the application of potassium nitrate or mono-potassium phosphate in comparison with control trees. The best result was obtained with potassium nitrate, probably due to the higher needs of N than P in olive nutrition. Centeno and Campo (2011) reported an increase

* Corresponding author. Tel.: +351 273 303237; fax: +351 273 325405.
*E-mail addresses:* angelor@ipb.pt (M.Â. Rodrigues), isabelaqferreira@gmail.com (I.Q. Ferreira), efmarilia@hotmail.com (A.M. Claro), marrobas@ipb.pt (M. Arrobas).
[1] Tel.: +351 273 303241; fax: +351 273 325405.
[2] Tel.: +351 273 303255; fax: +351 273 325405.

in olive yield after the application of N to the soil, and P and K as foliar sprays, even though initial leaf analysis indicated adequate nutrition levels.

In other studies, however, no significant responses of olive to fertilizers were recorded. In a two-year experiment, Marcelo et al. (2002) did not find significant differences in olive yield after the application of N and magnesium (Mg) as fertilizers, in comparison to the control unfertilized treatment. In a study carried out for five years in a mature olive orchard in the Southern of Spain, Fernández-Escobar et al. (2009b) did not find significant differences in olive yield between trees subjected to a fertilization program based on foliar diagnosis, and those receiving the current fertilization practice of the region [500 kg ha$^{-1}$ of a complex NPK (15:15:15) fertilizer plus three foliar sprays of micronutrients and aminoacids]. In long-term trials, carried out over thirteen years, Fernández-Escobar et al. (2009a) also found no differences between diverse N fertilization treatments (soil and foliar) and the non-fertilized control. In another study, Fernández-Escobar et al. (2012) estimated the balance of N in two olive orchards. Their results indicated that, under natural conditions represented by unfertilized plots, gains and losses were equivalent, which explain why leaf N concentrations remained above deficiency levels for many years, and also the lack of response in olive to N fertilization that they observed in previous studies.

Farmers, in turn, usually fertilize their groves apparently indifferent to the doubts that could persist about olive response to fertilizers. It seems inclusive that over-fertilization would not be uncommon, in particular for N. Annual applications of 80–200 kg N ha$^{-1}$ and more, are common in many areas of the Mediterranean basin (Fernández-Escobar, 2011). The excessive N rates used in agriculture are related to reduced nutrient-use efficiency and several environmental impacts on ecosystems (Raun and Schepers, 2008).

Fertilizer recommendations based on leaf analysis have been increasing. Plant analysis, however, presents some limitations. According to Righetti et al. (1990) plant analysis should be better viewed as a useful tool rather than as a means of making a rigid diagnosis. In addition, established threshold limits have been questioned. Fernández-Escobar et al. (2009a) question the deficiency threshold of 1.4% N in leaves because no reduction in yield or growth was observed for lower leaf N concentrations. The failure of leaf analysis to detect excess N was noted by Fernández-Escobar et al. (2011) after the observation of a rapid translocation of N from the younger olive leaves to storage organs. Righetti et al. (1990) consider that one should not expect strong significant relationships between mineral content and yield, growth or quality, in survey data. Standard values for many elements were derived from tissue analysis from high-producing orchards, since good nutrition is essential to obtain maximum production. However, other factors often limit yield even when nutrition is optimal.

Despite the important work that has been done on olive nutrition and fertilization, there still seems to be a long way to achieve a broad consensus among researchers, advisory laboratory heads and field consultants about the rates of fertilizer to apply to olive. It seems that a renewed effort should be put into methodologies that can improve the fertilizer recommendation systems. An interesting approach based on plant and soil gains and losses was performed by Fernández-Escobar et al. (2012) for N. In the present work, data are provided for almost all the essential plant nutrients. The total amount of nutrients in the different tree parts was estimated as a measure of its buffer capacity to provide nutrients from its own resources for the essential metabolic functions in periods where a shortage of soil nutrient supply could occur. The nutrients removed by crop and pruning were estimated as a measure of the main and regular losses from the system. A well managed olive orchard was selected to implement this experiment. It is grown under rainfed conditions, as is the majority of olive in the Mediterranean basin, and is ten years old, which ensures already good productions whilst allowing an easy and accurate estimation of the biomass and nutrients in the different parts of the tree.

## 2. Materials and methods

### 2.1. Experimental site characterization

The field experiment was carried out in north-eastern Portugal (Lombo, Macedo de Cavaleiros, 41°32′N, 6°58′W), in a dry farmed olive orchard (204 trees ha$^{-1}$) planted in a Leptosol derived from schist. The trees were ten years old of cv. Cobrançosa. It is a well-developed orchard when compared to others in this region of the same age. Every year in March, from the time of the initial planting of the orchard ten years ago, the farmer has applied a NPK fertilizer plus a boron-content fertilizer. In March 2010, the orchard was fertilized with 750 g tree$^{-1}$ of a compound 10:10:10 (10% N, $P_2O5$, $K_2O$) fertilizer and borax (11% B) at the rate of 5.0 g B tree$^{-1}$. The fertilizers were ground-applied and localized, but not excessively, under the canopies. Weeds were managed through the application of glyphosate (*N*-(phosphonomethyl)glycine; 360 g L$^{-1}$ of active ingredient, applied in a rate of 2 L ha$^{-1}$) early in April. The results of soil testing, performed in November 2010, and plant analysis, in January 2011, are presented in Table 1.

### 2.2. Crop harvest

Fourteen pre-selected trees with similar canopy sizes were used in this experiment. They were in an 'On' year in the biennial cycle of olive. The pre-selected trees were harvested in December 2010. A knapsack portable shaker-machine was used to pull the fruits down, and sheets on the floor were laid to recover them. Thereafter, the weights of olives were recorded per tree. Expressed per hectare, the crop reached a value of 2681 kg fresh fruit. Considering the age and canopy size of the trees, this production should be considered as high.

### 2.3. Pruning and records in the pruned material

In January 2010 the group of fourteen pre-selected trees was pruned. In this olive grove, pruning has been annually performed since it was planted. The farmer wants to withdraw annually about 20–30% of tree canopy to balance the vegetative and reproductive parts of the plant, to reduce the biennial bearing.

The trees included in this experiment were also pruned by the farmer that has been doing it since the orchard was planted. After pruning, five people independently estimated the percentage of canopy that had been removed in each tree by visual comparison with the branches remaining in the tree. The average of the five estimates was recorded as the percentage of canopy removed in pruning.

The material removed in pruning was separated in twigs with leaves, secondary branches and main branches. These three components were weighed green. Sub-samples of twigs with leaves were separated into their two components (twigs and leaves) and weighed green. The material was weighed again after drying in an oven-drier at 70 °C. This allowed the recording of the dry matter of twigs and leaves present in pruning material and in whole trees, considering the percentage of canopy that had been removed in pruning.

From sub-samples of secondary and main branches, selecting some of the thicker and thinner ones, measurements were taken of the diameter of the basal part. The sub-samples were separated into bark (periderm and secondary phloem), and wood, and the parts weighed green and after drying at 70 °C for a long period until

**Table 1**
Soil testing and leaf analysis performed at the beginning of the experiment.

| Soil testing | Beneath canopy | Between rows | Leaf analysis | |
|---|---|---|---|---|
| Texture | Sandy loam | Sandy loam | Nitrogen (g kg$^{-1}$) | 13.3 |
| Organic C (g kg$^{-1}$)[a] | 5.5 | 4.7 | Phosphorus (g kg$^{-1}$) | 0.9 |
| pH ($H_2O$)[b] | 5.5 | 5.8 | Potassium (g kg$^{-1}$) | 11.0 |
| pH (KCl)[c] | 4.2 | 4.3 | Calcium (g kg$^{-1}$) | 9.7 |
| Extractable P (mg kg$^{-1}$)[d] | 132.8 | 23.0 | Magnesium (g kg$^{-1}$) | 1.2 |
| Extractable K (mg kg$^{-1}$)[d] | 148.5 | 80.5 | Boron (mg kg$^{-1}$) | 26.2 |

[a] Walkley-Black.
[b] Soil/water, 1:2.5.
[c] Soil/KCl 2 M 1:2.5.
[d] Egner–Riehm (ammonium lactate–acetic acid).

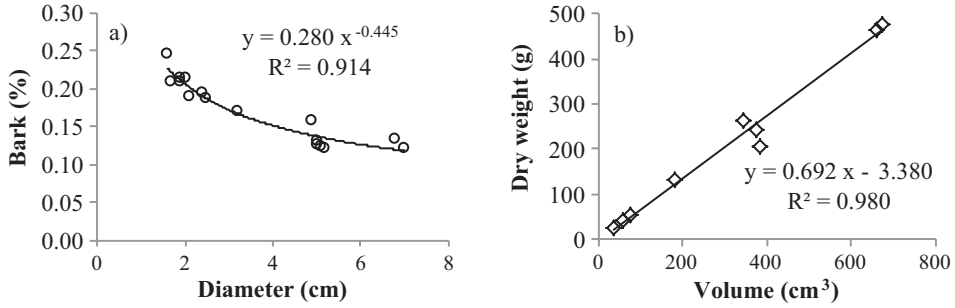


**Fig. 1.** Relationship between (a) the diameter of the base of branches and its percentage of bark and (b) the volume and dry weight of branches (not shelled).

a constant weight had been reached. In addition, the relationship between the diameter of the base of branches, and their percentage of bark as dry weight, was established (Fig. 1a). This made it possible to estimate the percentage of bark and wood in all plant components, including the trunk for which the results were extrapolated by using the equation presented in Fig. 1a.

Sub-samples of secondary and main branches were used to estimate their volumes and green weights. Volumes were obtained by immersion in water in a graduated container. After drying at 70 °C for a long period to a constant weight, the material was weighed and the relationship between volume and dry weight established (Fig. 1b).

### 2.4. Measurements in the trees

The perimeters of the trunks at soil level, and immediately below the division of the main branches, as well as the length of the trunks, were determined for the 14 selected trees. The methodology was repeated for the main and the secondary branches. This made it possible to estimate the volume of the different components of a tree. From the relationship between volumes and dry weights obtained from pruned material (Fig. 1b), it was possible to estimate the dry matter in all plant components, including the trunk.

### 2.5. Laboratory analyses

The dried sub-samples of leaves and twigs were ground and analysed for nitrogen, phosphorus, potassium, calcium (Ca), magnesium, boron, copper (Cu), Zinc (Zn), iron (Fe) and manganese (Mn) concentrations. Bark samples were subjected to a similar procedure and analysed for the same elements. The woody parts (main and secondary branches) were analysed from samples of sawdust recovered from those parts, after drying at 70 °C. Tissue analyses were performed by Kjeldahl (N), colorimetry (B and P), flame emission spectrometry (K) and atomic absorption spectrophotometry (Ca, Mg, Cu, Zn, Fe and Mn) methods (Walinga et al., 1989). Since there was not sawdust and bark available from the trunks, since that would imply the death of the tree, their nutrient concentrations were considered equal to that of the larger branches.

**Table 2**
Dry matter (mean ± SD) in the different parts of a tree and removed by pruning.

| | Total (kg) | Pruning (kg) |
|---|---|---|
| Leaves | 3.30 ± 1.40 | 0.84 ± 0.17 |
| Twigs | 1.21 ± 0.43 | 0.31 ± 0.06 |
| Sec. branches | | |
| Wood | 3.63 ± 1.42 | 0.94 ± 0.22 |
| Bark | 0.79 ± 0.31 | 0.20 ± 0.05 |
| Main branches | | |
| Wood | 1.45 ± 0.68 | 0.42 ± 0.25 |
| Bark | 0.19 ± 0.09 | 0.06 ± 0.03 |
| Trunk | | |
| Wood | 5.80 ± 1.01 | |
| Bark | 0.65 ± 0.09 | |
| Fruit | | |
| Pulp | 4.67 ± 1.09 | |
| Pit | 2.08 ± 0.49 | |
| Total | 23.76 ± 6.06 | 2.77 ± 0.67 |

Samples of olives were weighed green. The samples were divided into pulp and pit (including seed). Initially the pulp was removed from pits and part of it was used green for element nutrient determination, since the fat of the fruit does not allow the grinder to work. The water content was determined thereafter in the remaining pulp. The pits were cleared of debris pulp and weighed green. Thereafter they were dried, weighed, hammered to reduce hardness and ground. Nutrient concentrations in pits were determined in dried and ground material. The methodology allowed also the determination of the pulp-to-pit ratio, both green and dried.

## 3. Results

Total dry matter (DM) in a tree was 23.76 kg distributed by trunk (27.1%), main branches (6.9%), secondary branches (18.6%), twigs (5.1%), leaves (13.9%) and fruits (28.4%) (Table 2). In the pruning, there was removed 27.6% of branch (leaves, twigs,

secondary and main branches), representing an average of 2.77 kg DM. Leaves represented 30.3% of the DM removed, twigs 11.2%, secondary branches 41.2% and main branches 17.3%. The bark removed in pruning, excluding that was in twigs, represented 9.4% and wood 49.1%.

Mean N concentration in the leaves was 16.00 g kg$^{-1}$ (Table 3). Mean N concentration was also relatively high in twigs (6.58 g kg$^{-1}$) and bark (>6 g kg$^{-1}$), low in fruit (4.74 and 2.85 g kg$^{-1}$ in pulp and pit) and very low in woody parts (<2 g kg$^{-1}$). Phosphorus was present in the highest concentration in the pulp (1.33 g kg$^{-1}$). The leaves presented 1.02 g P kg$^{-1}$. Phosphorus concentrations in other tissues were low. The higher potassium concentrated tissues were leaves (7.20 g kg$^{-1}$), followed by twigs (7.17 g kg$^{-1}$) and pulp (6.83 g kg$^{-1}$). Mean Ca concentration in leaves was 15.98 g kg$^{-1}$. Bark was also a high Ca concentrated tissue (≥12 g kg$^{-1}$). The highest Mg concentration in tissues occurred in leaves (1.24 g kg$^{-1}$), followed by twigs (0.99 g kg$^{-1}$) and fruit (0.80 and 0.69 g kg$^{-1}$ in pulp and pit, respectively). Boron was present in a higher concentration in the pulp (43.82 mg kg$^{-1}$) than in any other plant tissue. Leaves, twigs and bark presented boron concentrations between 18 and 21 g kg$^{-1}$.

The above-ground part of a tree contains 119.37 g of N, 44.4% in leaves, 23.6% in fruits and only 25.4% in trunk, main and secondary branches together (Table 4). The 14.26 g of P contained in a tree were distributed primarily in fruits (49.6%), leaves (23.6%) and trunk, all branches and twigs (26.7%). Each tree contained 92.99 g of K. The higher K pool was fruits (39.4%) followed by leaves (25.4%). Forty eight percent of the 110.89 g Ca of a tree was in leaves. Fruits contain only 13.1% of the total Ca. The fruit was a high pool of Mg (37.8%). The leaves accounted for 30.2% Mg of a tree. The fruit was also the highest pool of B (51.1%). The leaves contained only 13.7% of the total B in a tree.

Total N removed in pruned material was 4.0 kg ha$^{-1}$, distributed by leaves (68.5%), twigs (10.5%), bark (8.8%) and wood (12.5%) (Table 5). Potassium and calcium were removed in the total amounts of 2.50 and 4.17 kg ha$^{-1}$, respectively, and phosphorus, magnesium and boron were removed in the amounts of 304.6, 361.1 and 7.9 g ha$^{-1}$. In pruned material, nutrients removed in leaves represented 57.5, 49.2, 65.9, 58.7 and 39.3%, respectively for P, K, Ca, Mg and B.

The pulp is higher pool than the pit for all the nutrients (Table 5). The olive yield recorded for the 14 trees included in the experiment permit the estimation of a crop of 2681 kg ha$^{-1}$. This crop removed 5.72, 1.44, 7.48, 2.97 and 1.06 kg ha$^{-1}$, respectively of N, P, K, Ca and Mg and 45.33 g ha$^{-1}$ of B.

Iron was presented in leaves at higher concentration (100.99 mg kg$^{-1}$) than Zn (57.75 mg kg$^{-1}$), Mn (45.37 mg kg$^{-1}$) or Cu (8.50 mg kg$^{-1}$) (Table 6). The crop removed 4.13, 119.75, 148.99 and 14.40 g ha$^{-1}$, respectively of Cu, Fe, Zn and Mn. In the pruning material, there were removed 8.90, 38.26, 20.69 and 36.61 g ha$^{-1}$ of Cu, Fe, Zn and Mn.

## 4. Discussion

### *4.1. Tissue nutrient concentration and nutrient distribution within the tree*

Leaves presented the highest N concentration among plant tissues, 16.0 g kg$^{-1}$, which represent 44.5% of total N in a tree. Nitrogen is an integral constituent of proteins, nucleic acids and many other organic structures of living cells (Scherer and Mengel, 2007) which explains its abundance in the leaves. Bark presented a fairly high N concentration, probably due to the presence in the phloem of organic acids and organically bound N, particularly in the form of amino acids and amides (Marschner, 1995). Fruit N concentration is lower than leaves. Previous studies had already shown that this is true for pome and stone fruits (Righetti et al., 1990). The fruit appears to be an important sink for N only in the initial phase of growth. As fruit size increases, N concentration decreases (Fernández-Escobar et al., 2011). The leaves and bark appear to be the tissues responsible for the buffering capacity of the tree to provide N for new growth.

The pulp of the fruit is the highest P concentrated tissue in a tree, followed by the leaves. Phosphorus is a constituent of macromolecular structures such as nucleic acids and various phosphophingolipids and coenzymes. As inorganic phosphate, it controls some key enzyme reactions (Scherer and Mengel, 2007). Total P in a tree was 14.26 g, 49.6% of which is in the fruit. In many crops a N:P of 10:1 is considered optimum for growth (Mills and Jones, 1996). In this orchard leaf N:P was 15.7:1 and total N:P was 8.4:1 due to the higher relative importance of P in fruit. Pruning wood removed only 304.63 g P ha$^{-1}$ and fruit 1.44 kg P ha$^{-1}$. Previous works have shown that P responses are rare in tree fruits (Righetti et al., 1990) and have not been clearly demonstrated for field-grown olive (Fernández-Escobar, 2008; Freeman and Carlson, 2005). The low P concentration in plant tissues and the limited P removed in fruit and pruning material may explain those results.

Leaf and fruit pulp K concentrations were, respectively, 7.20 and 6.82 g kg$^{-1}$. Potassium concentration in fruit pulp approximated to that of leaves, as happens with many pome and stone fruits (Righetti et al., 1990). At harvest, 40.0% of total K in a tree appeared in the fruit. Leaves contained only 25.4% of total K. Potassium is not a constituent of organic structures. It is involved in pH stabilization and osmoregulation, and is required for enzyme activation and membrane transport processes (Scherer and Mengel, 2007). Potassium is quite mobile both in the xylem and in the phloem (Marschner, 1995). The high K concentration in fruit supports the experimental evidences that alternate bearing cycles affect leaf K contents (Fernández-Escobar et al., 1999; Sibbett and Ferguson, 2002) and that a regular supply of K from soil should be ensured.

Leaf Ca concentrations were high in leaves (15.98 g kg$^{-1}$), bark (11.99–13.36 g kg$^{-1}$) and incomparably lower in fruit (2.03 and 2.44 g kg$^{-1}$ in pulp and pit). In fruit trees, the greater difference in nutrient concentration between foliage and fruits is usually noted with Ca (Righetti et al., 1990). The olive leaves stored 47.7% of total tree Ca and fruits (pulp plus pit) only 13.1%. Calcium is translocated in the xylem mainly through the transpiration stream. A lowering of transpiration rate further decreases the Ca content of fruits. Not in olives but in fruits of higher growth rates, there is a serious risk that Ca levels fall below the critical levels required for the maintenance of membrane integrity, leading to the typical Ca-deficiency-related disorders such as blossom end rot in tomato and bitter pit in apple (Marschner, 1995).

In an olive tree, the leaves were found to be the tissue presenting the highest Mg concentration. However, due to the relative importance of fruits in the total dry matter content of a tree, Mg stored in the fruits (5.18 g) was higher than that stored in the leaves (4.14 g). Magnesium is highly mobile in the phloem (Mills and Jones, 1996). Since fruits are dependent on the phloem for their mineral supply, they are proportionally higher in Mg than in Ca. The mobility of Mg and its relative abundance on fruits may justify the variation in leaf Mg concentrations that have been observed following the alternate bearing cycle of olive (Fernández-Escobar et al., 1999).

Boron concentration was the highest in fruit pulp and the lowest in the woody parts. Leaves and bark showed intermediate B concentrations. In a tree at harvest, 51.1% of total B was found in fruits. Boron moves primarily in the xylem, whilst the movement of B in the phloem is restricted (Brown and Shelp, 1997). However, boron is present in phloem and may be retranslocated in phloem often in sufficient amounts to satisfy the demands of developing sink regions that do not readily transpire (Brown and Shelp, 1997).

**Table 3**
Tissue nutrient concentrations (mean ± SD) in the different tree parts, expressed on dry matter basis.

| | | Nitrogen (g kg$^{-1}$) | Phosphorus (g kg$^{-1}$) | Potassium (g kg$^{-1}$) | Calcium (g kg$^{-1}$) | Magnesium (g kg$^{-1}$) | Boron (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Leaves | | 16.00 ± 0.72 | 1.02 ± 0.06 | 7.20 ± 0.90 | 15.98 ± 1.98 | 1.24 ± 0.32 | 18.08 ± 1.27 |
| Twigs | | 6.58 ± 0.75 | 0.87 ± 0.09 | 7.17 ± 0.44 | 6.45 ± 0.43 | 0.99 ± 0.19 | 18.15 ± 3.41 |
| Sec. branches | Wood | 1.76 ± 0.11 | 0.21 ± 0.03 | 1.78 ± 0.16 | 1.18 ± 0.05 | 0.26 ± 0.05 | 8.98 ± 0.84 |
| | Bark | 6.77 ± 0.60 | 0.31 ± 0.05 | 3.78 ± 0.60 | 11.99 ± 0.88 | 0.34 ± 0.05 | 21.91 ± 1.63 |
| Main branches | Wood | 1.86 ± 0.16 | 0.22 ± 0.03 | 1.80 ± 0.15 | 1.47 ± 0.16 | 0.24 ± 0.03 | 8.89 ± 0.70 |
| | Bark | 6.11 ± 0.70 | 0.26 ± 0.02 | 2.00 ± 0.68 | 13.36 ± 0.79 | 0.28 ± 0.03 | 20.32 ± 0.78 |
| Fruit | Pulp | 4.74 ± 0.72 | 1.33 ± 0.14 | 6.83 ± 1.90 | 2.03 ± 0.64 | 0.80 ± 0.19 | 43.82 ± 13.47 |
| | Pit | 2.85 ± 0.30 | 0.41 ± 0.06 | 2.03 ± 0.24 | 2.44 ± 0.40 | 0.69 ± 0.07 | 9.54 ± 1.93 |

**Table 4**
Nutrient distribution (mean ± SD) by different tree parts (values for an individual tree).

| | | Nitrogen (g) | Phosphorus (g) | Potassium (g) | Calcium (g) | Magnesium (g) | Boron (mg) |
|---|---|---|---|---|---|---|---|
| Leaves | | 53.14 ± 12.46 | 3.37 ± 0.71 | 23.62 ± 6.38 | 52.87 ± 10.59 | 4.14 ± 1.19 | 59.44 ± 14.44 |
| Twigs | | 7.89 ± 1.38 | 1.06 ± 0.21 | 8.64 ± 1.63 | 7.84 ± 2.17 | 1.22 ± 0.28 | 21.77 ± 4.25 |
| Sec. branches | Wood | 6.32 ± 1.14 | 0.76 ± 0.14 | 6.38 ± 1.18 | 4.29 ± 1.13 | 0.96 ± 0.27 | 32.45 ± 7.11 |
| | Bark | 5.38 ± 1.14 | 0.23 ± 0.03 | 2.96 ± 0.71 | 9.40 ± 1.70 | 0.26 ± 0.05 | 17.31 ± 3.03 |
| Main branches | Wood | 2.69 ± 0.64 | 0.30 ± 0.07 | 2.56 ± 0.71 | 2.12 ± 0.60 | 0.34 ± 0.12 | 12.78 ± 3.87 |
| | Bark | 1.19 ± 0.41 | 0.05 ± 0.02 | 0.38 ± 0.15 | 2.58 ± 0.71 | 0.05 ± 0.01 | 3.85 ± 0.99 |
| Trunk[a] | Wood | 10.77 ± 2.03 | 1.25 ± 0.16 | 10.47 ± 1.36 | 8.56 ± 0.198 | 1.38 ± 0.22 | 51.77 ± 7.60 |
| | Bark | 3.97 ± 0.79 | 0.17 ± 0.02 | 1.30 ± 0.33 | 8.66 ± 1.32 | 0.18 ± 0.04 | 13.16 ± 1.75 |
| Fruit | Flesh | 22.09 ± 3.84 | 6.20 ± 1.63 | 32.39 ± 6.51 | 9.55 ± 2.09 | 3.73 ± 0.97 | 202.38 ± 53.33 |
| | Pit | 5.94 ± 1.00 | 0.88 ± 0.26 | 4.27 ± 0.84 | 5.01 ± 0.95 | 1.45 ± 0.30 | 19.84 ± 4.29 |
| Total | | 119.37 ± 16.75 | 14.26 ± 2.18 | 92.99 ± 12.05 | 110.89 ± 15.55 | 13.71 ± 1.79 | 434.74 ± 70.92 |

[a] Estimated from nutrient concentrations of main branches.

**Table 5**
Nutrients removed by pruning wood and fruit (mean ± SD) per hectare.

| | | Nitrogen (kg) | Phosphorus (g) | Potassium (kg) | Calcium (kg) | Magnesium (g) | Boron (g) |
|---|---|---|---|---|---|---|---|
| Leaves | | 2.74 ± 0.57 | 175.29 ± 40.28 | 1.23 ± 0.30 | 2.75 ± 0.56 | 212.0 ± 35.22 | 3.09 ± 0.63 |
| Twigs | | 0.42 ± 0.09 | 55.40 ± 7.94 | 0.46 ± 0.10 | 0.41 ± 0.06 | 62.82 ± 14.61 | 1.16 ± 0.32 |
| Sec. branches | Wood | 0.33 ± 0.05 | 40.83 ± 8.43 | 0.34 ± 0.09 | 0.23 ± 0.04 | 48.86 ± 7.78 | 1.72 ± 0.35 |
| | Bark | 0.28 ± 0.06 | 12.46 ± 2.66 | 0.16 ± 0.05 | 0.49 ± 0.07 | 13.82 ± 2.43 | 0.90 ± 0.16 |
| Main branches | Wood | 0.16 ± 0.05 | 17.82 ± 4.76 | 0.15 ± 0.05 | 0.13 ± 0.04 | 20.45 ± 6.53 | 0.76 ± 0.28 |
| | Bark | 0.07 ± 0.02 | 2.82 ± 0.84 | 0.02 ± 0.01 | 0.16 ± 0.04 | 3.16 ± 1.13 | 0.23 ± 0.09 |
| Total | | 4.01 ± 0.83 | 304.63 ± 41.02 | 2.37 ± 0.51 | 4.17 ± 0.73 | 361.12 ± 52.69 | 7.86 ± 1.50 |
| Fruit | Flesh | 4.51 ± 0.87 | 1265.76 ± 236.65 | 6.61 ± 1.68 | 1.95 ± 0.56 | 761.32 ± 160.95 | 41.29 ± 9.05 |
| | Pit | 1.21 ± 0.32 | 178.91 ± 34.35 | 0.87 ± 0.20 | 1.02 ± 0.24 | 296.16 ± 41.90 | 4.05 ± 0.94 |
| Total | | 5.72 ± 1.60 | 1444.67 ± 257.08 | 7.48 ± 1.74 | 2.97 ± 0.67 | 1057.48 ± 171.04 | 45.33 ± 9.52 |

**Table 6**
Trace element concentration (mean ± SD) in the leaves and removed in pruned material and fruit.

| | Copper | Iron | Zinc | Manganese |
|---|---|---|---|---|
| Leaf (mg kg$^{-1}$) | 8.50 ± 2.58 | 100.99 ± 11.85 | 57.75 ± 36.15 | 45.37 ± 22.45 |
| Fruit (g ha$^{-1}$) | 4.13 ± 0.46 | 119.75 ± 17.02 | 147.99 ± 64.23 | 14.40 ± 4.66 |
| Pruned material (g ha$^{-1}$) | 8.90 ± 0.71 | 38.26 ± 6.67 | 20.69 ± 3.57 | 36.61 ± 3.74 |

Almond had also highest B concentration in hull (fruit tissue) with much lower B in the leaves (Brown and Shelp, 1997). Indirect evidence also exists that olive fruits are an important sink for B. It has been observed that leaf B concentrations in winter are substantially lower than in summer (Arrobas et al., 2010; Rodrigues et al., 2011), reflecting the drain of B from leaves to the fruits.

Leaf Fe, Zn, Mn and Cu concentrations found in this orchard can be considered as normal or high in comparison to the threshold limits established for the crop (Fernández-Escobar, 2008) and other published results (Chatzistathis et al., 2010), probably reflecting the low soil pH (Table 1). Most of the situations of Fe, Mn and Zn deficiencies reported in the literature were from trees grown in calcareous soils (Righetti et al., 1990). Deficiency and toxicity levels of Cu, Fe, Zn, and Mn were not expected to occur in well aerated soils with a pH close to neutrality, and usual fertilizer recommendations do not include Cu, Fe, Zn or Mn. Lime applications and soil drainage are the most common strategies to overcome situations of toxicity of these elements. Deficiency levels may be corrected by applying the nutrient as synthetic chelates or other forms to the soil or as foliar sprays (Havlin et al., 2005), or injected directly into the trunk, as proposed by Fernández-Escobar et al. (1993) to supply Fe in situations of lime-induced chlorosis.

### 4.2. Guidelines for fertilizer recommendations

Most farmers remove pruning wood from the orchards since it is an important fuel for burning in fireplaces. In other situations, though less frequent, pruning wood is shredded and left on the floor. These aspects can be taken into account in fertilizer advisory systems. Here we assume that the pruning wood is removed from the orchard.

Nitrogen removed in the olive crop and pruning reached 9.7 kg N $ha^{-1}$. Considering that almost all farmers apply the fertilizers late in winter or early spring, after the heavier rains, N use efficiency is expected to be high. Using 50–75% as reference for N use efficiency, the annual N rate should be between 13 and 19 kg N $ha^{-1}$. Available information provided by reference laboratories indicates that they usually recommend greater amounts of N. LQARS (2006), for instance, advise a range of 15–60 kg N $ha^{-1}$ for young orchards (1–5 years) and 0–130 kg N $ha^{-1}$ for mature orchards grown in rainfed conditions, depending on crop load and current leaf N concentration. Garcia (2009) recommends 0.5–1.0 kg N $tree^{-1}$, with a maximum of 150 kg N $ha^{-1}$, based mainly on nutrients removed in olives. The results here presented suggest that one should be more conservative regarding N applications and 130 and 150 kg N $ha^{-1}$ appears as unacceptably high values to be used in non-irrigated olive orchards. Crop load or alternate fruiting of a given orchard is not a valid reason to alter N rate. In 'On' years, the photoassimilates are derived primarily to the fruits whose growth needs less N than leaves. To grow more leaves, which occur in 'Off' years, requires much more N (Righetti et al., 1990). In addition, the buffer capacity of the plant permits that crop is not affected in the short-term. Thus, what is important in an olive orchard is to know its average yield potential. In young orchards, the need for additional N to build up the permanent structure of the trees seems to be of little relevance. Each tree retained only in its ten years of life an average of 92 g N, which represents 1.86 kg N $ha^{-1}$ $year^{-1}$. Thus, in olive, N should be applied at conservative rates. After defining the N rate, the transient nature of N in soil requires that it should be applied every year to increase nutrient use efficiency. Leaf analysis should be further performed as an aid to monitor and adjust N rates over the years.

The fruit and pruning wood removed 1.75 kg P $ha^{-1}$. Expressed as $P_2O_5$, this represents 4.0 kg $ha^{-1}$ $year^{-1}$. The low P exportation level may explain the lack of response of olive to P application as fertilizer that has been observed in field trials. The result also suggests that regular P applications would not be necessary, in agreement with general opinion (Fernández-Escobar, 2008; Freeman and Carlson, 2005). Phosphorus application should be dependent on a previous demonstration (soil testing and plant analysis) that the soil does not supply enough P for an adequate plant growth.

To replenish the K exported by fruits and pruning, an average annual application of 9.9 kg K (11.9 kg $K_2O$) $ha^{-1}$ should be provided. LQARS (2006) recommends 0–240 kg $K_2O$ $ha^{-1}$, depending on yield goal, current plant analysis results and soil fertility. Garcia (2009) recommends 1–2 kg $K_2O$ $tree^{-1}$, based mainly on nutrients removed in olives. In spite of being well documented that K is often a nutritional problem in olive orchards (Freeman and Carlson, 2005; Fernández-Escobar, 2008), high fertilizer rates would not be necessary. Potassium is present in soil in structural components of primary and secondary minerals, fixed in the lattice of clay minerals, adsorbed in the surface of soil colloids and as a solute in soil solution (Havlin et al., 2005). The need for a regular application of K and the amount that should be applied in each application depends on soil K availability and on the soil capability to retain it adsorbed in colloids or fixed in clay minerals. In sandy soils, for instance, the strategy for K application should be similar to that of N, based on a regular application of a limited amount of fertilizer. In clay soils, in turn, it is possible to apply higher amounts with less frequent applications. The method of K application, soil or foliar, does not seem to affect the effectiveness of K fertilization (Restrepo-Díaz et al., 2008).

In a year were removed from the system 7.1 kg Ca $ha^{-1}$ and 1.4 kg Mg $ha^{-1}$. However, the need for Ca applications as fertilizer is usually restricted to highly acid soils. A Mg deficiency disorder may occur through ionic antagonism induced by other cations such as $Ca^{++}$, $K^+$, $NH_4^+$ or $H^+$ (Marschner, 1995). In practice, an Mg deficiency disorder may also occur in sandy, acid soils or after the application of calcium carbonate lime or high rates of K fertilizers (Freeman and Carlson, 2005). It seems that Ca and Mg should not be a serious problem in most olive groves, since Ca and Mg occur in soil solution in great abundance (Freeman and Carlson, 2005).

Boron was removed in the crop and pruning wood in an amount of 53.3 g $ha^{-1}$. This small quantity may suggest that B would not be a concern in the fertilization of this crop. However, both LQARS (2006) and Garcia (2009) recommend B application "if needed". Garcia (2009) proposes a balance between macronutrients and B of 20:8:14:0.1 (N, $P_2O_5$, $K_2O$, B). The need for a regular B application should be sought in the behaviour of B in the soil and in the plant. Boron is unique among the essential plant nutrients in that it has restricted mobility in many plant species and is freely mobile in others (Brown and Shelp, 1997). In olive, significant remobilization of B probably only occurs from leaves to flowers and fruits, as demonstrated in previous studies (Perica et al., 2002; Delgado et al., 1994). Growing tips would not be able to attract B remobilized from older leaves, since in olive they are the first tissue showing B deficiency symptoms, at least for the majority of the olive cultivars. Thus, a regular supply of B may be needed independently to the amount of B exported annually in fruits and pruning wood. The behaviour of B in soils is totally different. In soils, B presents great mobility. Under high rainfall conditions, B is readily leached from soil as $B(OH)_3$ (Marschner, 1995). It seems that a sound B fertilization strategy consists of the application of small amounts of the nutrient every year, in orchards that have been previously demonstrated that the soil do not supply enough B for the regular growth of the trees.

## 5. Conclusions

Nutrients removed from crop and pruning suggest that one should be very conservative regarding fertilizer applications in olive. In young orchards of a yield close to 2500 kg fruit $ha^{-1}$, 15–18 kg N $ha^{-1}$ $year^{-1}$ seems to be an adequate N rate to balance the N annually exported. For higher producing orchards and those with higher canopy size, N rates should be proportionally increased. The transient nature of N in the soil/plant system recommends annual fertilizer applications to increase N use efficiency. Potassium, P, Ca, Mg and B should only be applied if their needs are demonstrated through soil testing and plant analysis. Boron, if needed, should also be applied every year, due to its behaviour in soil and within the plant, albeit at low rates. An application of the other nutrients can last several years, except K in sandy soils which should also be applied every year. Soil testing and leaf analysis should be used routinely to monitor changes in the nutrient level, and to adjust the fertilization program.

## Acknowledgment

Supported by FEDER funds through the Operational Programme for Competitiveness Factors – COMPETE, and national funds through FCT – Foundation on Science and Technology under the project PTDC/AGR-AAM/098326/2008.

## References

Arrobas, M., Lopes, J.I., Pavão, F., Cabanas, J.E., Rodrigues, M.A., 2010. Comparative boron nutritional diagnosis for olive based on July and January leaf samplings. Commun. Soil Sci. Plant Anal. 41, 709–720.

Brown, P.H., Shelp, B.J., 1997. Boron mobility in plants. Plant Soil 193, 85–101.

Centeno, A., Campo, M.G., 2011. Response of mature olive trees with adequate leaf nutrient status to additional nitrogen, phosphorus and potassium fertilization. Acta Hort. 888, 277–280.

Chatzistathis, Th., Therios, I., Alifragis, D., Dimassi, K., 2010. Effect of sampling time and soil type on Mn, Fe, Zn, Ca, Mg, K and P concentrations of olive (*Olea europaea* L., cv. 'Koroneiki') leaves. Sci. Hort. 126, 291–296.

Delgado, A., Benlloch, M., Fernández-Escobar, R., 1994. Mobilization of boron in olive trees during flowering and fruit development. HortScience 29 (6), 616–618.
Fernández-Escobar, R., 2008. Fertilización. In: Barranco, D., Fernández-Escobar, R., Rallo, L. (Eds.), El Cultivo del Olivo. Mundi-Prensa, Madrid, pp. 299–336.
Fernández-Escobar, R., 2011. Use and abuse of nitrogen in olive fertilization. Acta Hort. 888, 249–257.
Fernández-Escobar, R., Barranco, D., Benlloch, M., 1993. Overcoming iron chlorosis in olive and peach trees using a low-pressure trunk-injection method. HortScience 28, 192–194.
Fernández-Escobar, R., García-Novelo, J.M., Molina-Soria, C., Parra, M.A., 2012. An approach to nitrogen balance in olive orchards. Sci. Hort. 135, 219–226.
Fernández-Escobar, R., Garcia-Novelo, J.M., Restrepo-Díaz, H., 2011. Mobilization of nitrogen in the olive bearing shots and after foliar application of urea. Sci. Hort. 127, 452–454.
Fernández-Escobar, R., Marin, L., Sánchez-Zamora, M.A., García-Novelo, J.M., Molina-Soria, C., Parra, M.A., 2009a. Long-term effects of N fertilization on cropping and growth of olive trees and on N accumulation in soil profile. Eur. J. Agron. 31, 223–232.
Fernández-Escobar, R., Moreno, R., Garcia-Creus, M., 1999. Seasonal changes of mineral nutrients in olive leaves during the alternate-bearing cycle. Sci. Hort. 82, 25–45.
Fernández-Escobar, R., Parra, M.A., Navarro, C., Arquero, O., 2009b. Foliar diagnosis as a guide to olive fertilization. Span. J. Agric. Res. 7 (1), 212–223.
Freeman, M., Carlson, R.M., 2005. Mineral nutrient availability. In: Sibbett, G.S., Ferguson, L. (Eds.), Olive Production Manual, 3353, 2nd ed. University of California Publication, Oakland, CA, pp. 75–82.
Garcia, C.G., 2009. Abonado del olivar. In: Guia Práctica de la Fertilización Racional de los Cultivos en España. Ministerio de Medio Ambiente y Medio Rural y Marino, Madrid, España, pp. 223–233.
Hartmann, H.T., Uriu, K., Lilleland, O., 1966. Olive nutrition. In: Childers, N.F. (Ed.), Temperate to Tropical Fruit Nutrition. Hort. Publ. Rutgers Univ., New Brunswick, N.J, pp. 252–261.
Havlin, J.L., Beaton, J.D., Tisdale, S.L., Nelson, W.L., 2005. Soil Fertility and Fertilizers. An Introduction to Nutrient Management, 2nd ed. Pearson Prentice Hall, New Jersey.
Jasrotia, A., Singh, R.P., Singh, J.M., Bhutami, V.P., 1999. Response of olive trees to varying levels of N and K fertilizers. Acta Hort. 474, 337–340.
Larbi, A., Gargouri, K., Ayadi, M., Dhiab, A.B., Msallem, M., 2011. Effect of foliar boron application on growth, reproduction, and oil quality of olive trees conducted under a high density planting system. J. Plant Nutr. 3, 2083–2094.
LQARS (Laboratório Químico Agrícola Rebelo da Silva), 2006. Manual de Fertilização de Culturas. INIAP, LQARS, Lisboa, Portugal.
Marcelo, M.E., Jordão, P.V., Soveral-Dias, J.C., Matias, H., Rogado, B., 2002. Effect of nitrogen and magnesium application on yield and leaf N and Mg concentrations of olive trees cv. Picual. Acta Hort. 586, 329–332.
Marschner, H., 1995. Mineral Nutrition of Higher Plants, 2nd ed. Academic Press, New York.
Mills, H.A., Jones Jr., J.B., 1996. Plant Analysis Handbook II. MicroMacro Publishing Inc., Athens, GA.
Perica, J., Brown, P.H., Connell, J.H., Hu, H., 2002. Olive response to foliar B application. Acta Hort. 586, 381–382.
Raun, W.R., Schepers, J.S., 2008. Nitrogem management for improved use efficiency. In: Schepers, J.S., Raun, W.R. (Eds.), Nitrogen in Agricultural Systems. Agronomy Monograph No. 49. ASA, SSSA, CSSA, Madison, WI, pp. 675–693.
Restrepo-Díaz, H., Benlloch, M., Navarro, C., Fernández-Escobar, R., 2008. Potassium fertilization of rainfed olive orchards. Sci. Hort. 116, 339–403.
Righetti, T.L., Wilder, K.L., Cummings, G.A., 1990. Plant analysis as an aid in fertilizing orchards. In: Westermann, R.L. (Ed.), Soil Testing and Plant Analysis. , 3rd ed. Book Series no. 3. SSSA, Madison, WI, pp. 563–601.
Rodrigues, M.A., Pavão, F., Lopes, J.I., Gomes, V., Arrobas, M., Moutinho-Pereira, J., Ruivo, S., Cabanas, J.E., Correia, C.M., 2011. Olive yields and tree nutritional status during a four year period without nitrogen and boron fertilization. Commun. Soil Sci. Plant Anal. 42 (7), 803–814.
Sarrwy, S.M.A., Mohamed, E.A., Hassan, H.S.A., 2010. Effect of foliar sprays with potassium nitrate and mono-potassium phosphate on leaf mineral contents, fruit set, yield and fruit quality of Picual olive trees grown under sandy soil conditions. Am.-Euras. J. Agric. Environ. Sci. 8 (4), 420–430.
Scherer, H.W., Mengel, K., 2007. Ullmann's Agrochemicals. Fertilizers, vol. 3. Wiley-VCH Verlag GmbH & Co, KGaA, Weinheim (Chapter 2).
Sibbett, G.S., Ferguson, L., 2002. Nitrogen, boron, and potassium dynamic in 'On' vs 'Off' cropped Manzanillo olive trees in California, USA. Acta Hort. 586, 369–373.
Soyergin, S., 2010. Effects of soil and leaf treatments to eliminate boron deficiency in olives. Commun. Soil Sci. Plant Anal. 41, 2004–2010.
Walinga, I., van Vark, W., Houba, V., van der Lee, J., 1989. Soil and Plant Analysis. Part 7 – Plant Analysis Procedures. Wageningen Agricultural University, The Netherlands.