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Long-Term Impact of Potassium Fertilization on Soil and Productivity in Intensive Olive Cultivation

Amnon Haberman [1,2], Arnon Dag [1], Nerya Shtern [1], Isaac Zipori [1], Ran Erel [1], Alon Ben-Gal [1] and Uri Yermiyahu [1,*]

[1] Gilat Research Center, Agricultural Research Organization, M.P. Negev 85280, Gilat, Israel
[2] CSIRO Agriculture and Food, Locked Bag 2, Glen Osmond, South Australia 5065, Australia
* Correspondence: uri4@volcani.agri.gov.il; Tel.: +972-8-992-8649

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Abstract: The olive growing sector is transitioning from traditional to intensive irrigated cultivation, dictating a need to reconsider orchard management practices including fertilization. Potassium (K) is an essential nutrient, typically found in high concentrations in plants. Orchard K fertilization requirements are commonly derived from the disparity between assumed tree requirements and extractable soil K. The long-term impact of insufficient fertilization on K available in the soil, growth, and yield of irrigated field-grown olive trees was evaluated over six consecutive seasons. Withholding of K fertilization led to lower exchangeable and soluble K concentrations in the soil and significantly impaired yield. The reduction in yield was attributed to reduced flowering and fruit set, resulting in a lower fruit number. Tree vegetative growth and flowering quality traits were not affected. In addition, trees not receiving K appeared to be more susceptible to alternate bearing. Following two seasons of omitting K fertilization, leaf K concentration did not decrease below the conventionally accepted sufficiency threshold for olive (0.8%). In spite of this, the trees produced significantly lower yields. Our results suggest that long-term insufficient K fertilization results in reduced soil available K and consequently impairs tree productivity. The results imply that the sufficiency threshold for K in diagnostic leaves should be reconsidered for intensive orchards. Moreover, the current method for K deficiency detection using leaf K concentration may be inadequate for intensive orchards. Integration of other parameters, such as fruit K content, leaf Na, and changes in soil exchangeable K content or sorption energy, may promote a more reliable analysis of orchard K nutritional status.

Keywords: olive; *Olea europaea*; fertigation; fertilization; yield; fruit set; flowering; potassium; sodium

1. Introduction

Orchard management includes a number of aspects that determine productivity. In many cases, the dominant limiting variable for productivity in rain-fed olive (*Olea europaea* L.) orchards is water availability [1]. However, in modern intensive cultivation, which incorporates irrigation systems, water availability may no longer be a limiting factor. Following Liebig's law of the minimum, the yield will be determined by the next dominant limiting factor, possibly nutrient availability. Accordingly, fertilization, in most cases with nutrients supplied via the irrigation system ("fertigation") is a common practice in intensive irrigated agriculture [2].

Potassium (K) fertilization is a common practice supporting sustainable crop production in intensive agriculture [3]. Generally, plants require large quantities of K, and hence, K is classified as a 'macro'- nutrient [4]. Potassium is involved in several vital physiological processes and is known to influence various aspects of product quality [3,5]. Potassium plays fundamental roles in plant water management and osmoregulation and is thought to be important for plant stress tolerance to abiotic stress causing factors including drought, salinity, and radiation [6].

Plants with minor K deficiencies may suffer from reduced growth and productivity, while not necessarily exhibiting visible symptoms. Severe K deficiency may lead to leaf chlorosis and necrosis [7]. Potassium deficiency is considered the most frequent olive nutritional disorder, particularly in rain-fed orchards [8,9]. Symptoms of K deficiency in olives include leaf tip necrosis, defoliation, and small and wrinkled fruit [9]. Potassium deficiencies are usually diagnosed via foliar analysis of K in July. Concentrations under 0.4% are suggested to indicate a severe deficiency, and above 0.8% is considered sufficient [9,10].

Plants absorb K from the soil through the root system [11]. Soil K persists in four distinct pools: soil solution, exchangeable, slowly exchangeable, and structural K [12]. The immediately available K to the plant roots is mostly from the soil solution; however, this pool represents only a small fraction of the total K in the soil, and generally cannot meet crop demand [7] without being replenished. The exchangeable and slowly exchangeable K pools are the source for soil solution K replenishment, allowing for sufficient plant uptake [7]. The structural K pool (in soil minerals) usually holds the majority of the soil's K (90–98%). However, the release rate of K from this pool is very low [7], and therefore, is hardly available to plant roots [13].

In olive cultivation, K is estimated to have the highest offtake rate, with an average removal of 10.9 kg per ton of fruit dry weight [14]. Xiloyannis et al. [15] estimated that the annual K demand in a six-year-old irrigated olive orchard is 81.5 kg ha^{-1} (cv. Coratina). Under high fruit load ('On year'), leaf K concentration significantly decreases during the time of fruit development, suggesting that K may be important for fruit production [16]. Consequentially, K fertilization is a common practice in most olive orchards, aimed to support the supply from the soil to meet tree requirements.

Several studies have demonstrated the positive effect of K application on leaf K concentration. However, in many cases, this effect did not influence tree performance [17–19]. Hussein [20] reported that the application of increasing K levels by fertigation lead to improved vegetative growth and fruit yield in Manzanillo olives growing on sandy soil. In addition to soil application, K foliar sprays have been suggested as an effective means for correcting deficiencies, particularly in rain-fed orchards [9,17,21].

In a study with young olive trees growing in containers, subjecting trees to six K levels, K concentrations in diagnostic leaves were greatly affected, ranging from 0.22 to 1.64%. However, the K availability had only a marginal effect on tree growth and productivity, as opposed to nitrogen (N) and phosphorus (P), which had a considerable effect [22,23]. The lowest K level in this study, where leaf K concentrations were extremely low (0.22%), initiated a reduction in tree vigor and yield only in the third year of study [23]. Similarly, Hartmann and Brown [24] demonstrated that olive trees growing in containers without K for two years had very low levels of K in leaves, but did not present deficiency symptoms.

Recommendations for annual K soil fertilization range between 0.8–1.5 kg $tree^{-1}$ depending on soil type, tree size, irrigation practice, and leaf analysis [8,9]. Potassium availability and its uptake by the tree is strongly affected by the irrigation and water availability [20,25]. However, the majority of studies on the response of olive trees to K fertilization were performed in rain-fed orchards, and frequently, tree performance was not significantly affected [17–19]. Scientifically-based guidelines for K fertilization and identification of deficiencies in intensive irrigated olive cultivation are hardly available. We, therefore, studied the impact of K deficient fertilization on soil properties and long-term performance of trees in an intensive agro-system.

2. Materials and Methods

2.1. Experimental Site and Design

The experiment was performed in a commercial olive orchard located in the southern coastal plain of Israel (31°39′7.50″ N 34°40′54.00″ E). The orchard was planted in 2007 with trees of the cultivar Barnea [26] at a density of 360 trees ha^{-1} (4 m × 7 m). Orchard soil texture ranged from loam to clay loam, with average soil saturated paste extract pH value of 7.6. Orchard soil physical and chemical properties are presented as supplementary material (Table S1).

Trees were irrigated through a drip system with freshwater (EC = 0.4–0.5 dS m^{-1}) twice a week during the dry seasons, typically from March to October. The weekly irrigation amounts were set according to potential evapotranspiration, calculated by a modified Penman-Monteith method [27], and multiplied by a crop coefficient, which ranged during the season between 0.27–0.70. Annual irrigation volume in the years of the experiment was 470–630 mm and winter precipitation was 280–600 mm (average 460 mm). Meteorological data (precipitation and temperature) for the duration of the experiment is presented as supplementary material (Figure S1).

Trees were fertilized continuously through the irrigation system (fertigation), starting at the initiation of the irrigation season, throughout each irrigation until the annual fertilizer amount was completed, typically by late August. Two K treatments were studied: no additional K in fertigation (K0) and an annual application of 250 kg K ha^{-1} (K250). Israel Chemicals Ltd. (ICL) supplied the fertilizer solutions, which were compiled so that seasonal application per ha included: 150 kg N, 35 kg P, and 250 kg K (or none). Micronutrients were also supplied by fertigation at rates of 3.8 kg iron (Fe), 1.9 kg zinc (Zn), 940 g manganese (Mn), 140 g copper (Cu) and 100 g molybdenum (Mo). Based on the amounts of fertilizer and water applied, average N, P and K concentrations in the irrigation water were approximately 30, 7, and 50 mg L^{-1}, respectively (for the K250 treatment). The macro and micronutrient application doses were determined according to the common commercial practice for a mature intensive olive orchard in Israel [28].

The average measured K concentration in the irrigation water prior to adding fertilizers was 3.4 mg L^{-1}. Thus, according to the average amount of water applied (550 mm), the annual basal contribution of K from the irrigation water, and therefore, the amount of K in treatment K0 was about 19 kg ha^{-1}.

Plots of 12 uniform trees (three rows × four trees in the rows) were selected within a three ha area of the orchard, and two trees in the center of each plot were surveyed. The experiment was set up in randomized blocks with seven plots per treatment level, generating 14 surveyed trees per level (biological replications). The experiment was initiated on June 2011 and conducted over six consecutive seasons through the end of the 2016 season.

2.2. Measurements

2.2.1. Soil Analysis

Soil from each plot, under the drip-line of the surveyed trees, was sampled from three depths (0–30, 30–60, 60–90 cm), every spring and autumn at about the time of the beginning and end of the irrigation seasons (March and September). Soil exchangeable K content was determined by ammonium acetate extraction [29], and soluble K content was determined in saturated soil paste extracts. Potassium concentrations were determined by an atomic absorption spectrometer (AAnalyst 200, Perkin-Elmer, Waltham, MA, USA).

2.2.2. Leaf and Fruit Minerals Concentrations

For leaf analysis, about 100 fully expanded leaves of current season growth were sampled per tree during each July from non-bearing shoots (diagnostic leaves). Samples were oven-dried (70 °C), milled to a powder and digested with sulfuric acid and hydrogen peroxide (Merck, Darmstadt, Germany) [30]. Nitrogen and P concentrations were determined colorimetrically (Gallery Plus Automated Photometric Analyzer, Thermo Scientific, Waltham, MA, USA). Potassium and Na concentrations were determined by an atomic absorption spectrometer (AAnalyst 200, Perkin-Elmer, Waltham, MA, USA). For fruit analysis, samples were collected at harvest, crushed to paste, and handled similarly to the leaf samples.

2.2.3. Vegetative Growth Quantification

Tree trunk circumference was measured at a marked location 50 cm above ground every spring from 2011 to 2017, and the relative increase in circumference over the six years was calculated. Every season after harvest (January–February), a professional crew pruned the trees to the same canopy size, and in the 2012–2015 seasons, the pruning material was collected, chopped, and weighed separately for each tree.

2.2.4. Flowering and Fruit Set Assessment

At flowering time, trees were assessed visually for flowering intensity and scored on a scale of 0–5, with 5 representing the highest level. In addition, flowering intensities in 2014–2015 seasons were also estimated by quantifying the rate of buds initiating an inflorescence. In each tree, six shoots were selected before flowering initiation (December), and at flowering time, the rate of buds initiating an inflorescence was determined.

The numbers of flowers in an inflorescence, rate of perfect flowers, and flower pistil weight were evaluated in a sample of 10 inflorescences collected at flowering from each tree. For the estimation of the fruit set rate, six shoots were selected at flowering time in each tree and the number of inflorescences in the shoots was recorded. Three months later, the number of fruits in each shoot was counted, and the rate of fruit set (fruits per flower) was calculated using the number of inflorescences in each shoot and the mean number of flowers in an inflorescence.

2.2.5. Yields

When about 50% of the fruit started turning from green to purple, the fruit was harvested using a mechanical trunk-shaker with the assistance of rod beating, and the fruit yield was weighed separately per tree. The weight of a single fruit was assessed from a sample of 100 fruits per tree. Fruit oil content was determined from a sample of fruit crushed to paste in a laboratory mill (Abencor System; mc2, Ingenieria y Sistemas, Seville, Spain), and analyzed by calibrated near-infrared analysis (OliveScan, Foss, Hilleroed, Denmark) [31].

2.3. Data Analysis

Data were analyzed by one-way analysis of variance (ANOVA), using the JMP software (SAS Institute, Cary, NC, USA). Significant differences were determined according to Student's *t*-test, with $p \leq 0.05$. The alternate bearing index was calculated according to Monselise and Goldschmidt [32] with seasonal yields of individual trees. The ΔF value ($\Delta F = RT \ln K/\sqrt{(Ca + Mg)}$, R = 1.987, T = 298) was calculated with K, Ca, and Mg concentrations in saturated paste extracts. The change in soil exchangeable K per area unit (kg ha^{-1}) was calculated according to the assumptions: (1) soil bulk density is homogenous at 1.45 kg L^{-1}; (2) the horizontal flow of irrigation water from the emitters is 1.5 m, which means that 43% of the soil surface was affected by the irrigation. Accordingly, an increase of 1 meq kg^{-1} in 0.3 m soil layers equals 7.3 kg K ($1 \times 39(mg/mmol) \times 300m^3 \times 1.45\ ton/m^3) \times 43\%$). The fruit yield K offtake was calculated according to 360 trees ha^{-1} and an estimate for dry fruit weight of 50% with the seasonal fruit yields and fruit K concentrations data presented in Table S2.

To overcome delays in the treatment effects due to initial K reserves in the trees and soil, the early seasons of treatment implementation are omitted from the analysis of some parameters (soil saturated paste K content, flowering, fruit set and yields). In order to normalize the effects of alternate bearing, means of pruning material weight, yields, fruit size, and flowering intensity were calculated with data of two or four consecutive seasons. To overcome the variance resulting from the flowering intensity, analysis of the number of flowers in an inflorescence, rates of perfect flowers and fruit set is performed only with trees that flowered at medium to high intensities.

3. Results

3.1. Soil K Content

Throughout the experiment, soil saturated paste K content was significantly higher in the K fertilized plots (K250), at both the beginning (March) and end of the irrigation seasons (September; Figure 1a,b). This effect was most prominent in the upper soil layer (0–30 cm), while at the end of the irrigation seasons, K fertilization also had a significant positive effect in the next deepest layer (30–60 cm; Figure 1b). Soil saturated paste K content was significantly higher at the end of the irrigation seasons relative to the beginning of the irrigation seasons, with or without the K fertilization (Figure 1a,b).

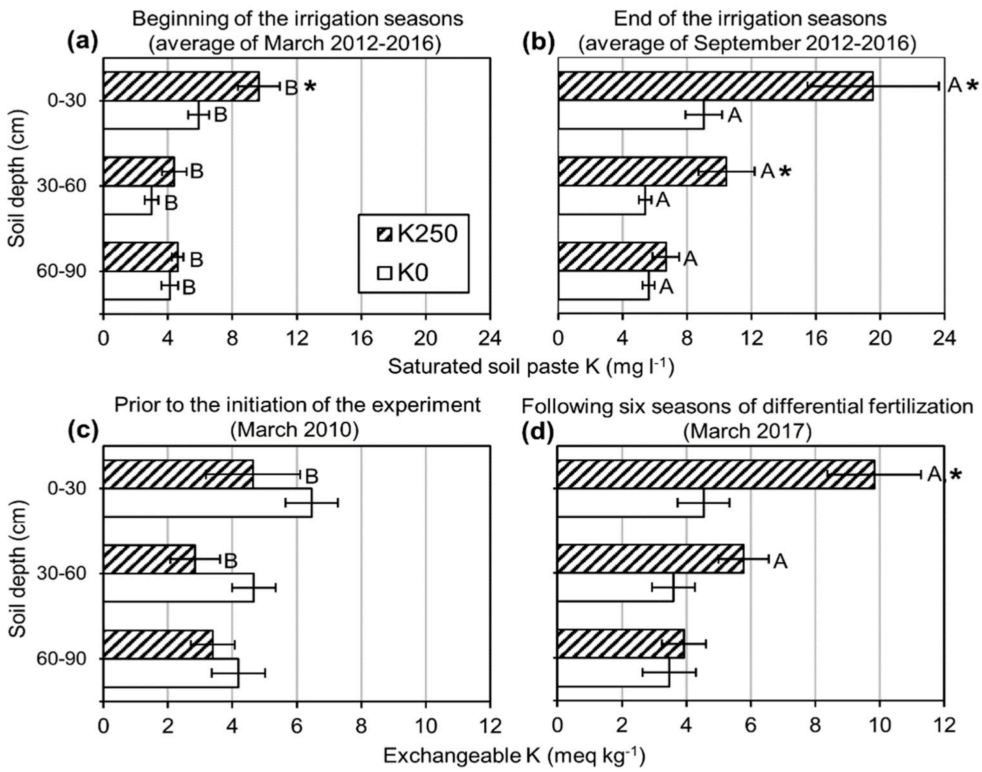

Figure 1. Influence of K fertilization on soil saturated paste K content and soil exchangeable K. Experiment plots were fertilized from 2011 season either with an annual amount of 250 kg K ha^{-1} (K250) or without K (K0). (**a**,**b**) Saturated soil paste K mean contents calculated for March (**a**) or September (**b**) sampling dates in 2012–2016 seasons. (**c**,**d**) Soil exchangeable K content prior to the initiation of the experiment (**c**; March 2010) and following six seasons of differential fertilization (**d**; March 2017). Numbers are mean values of seven replicates (plots) ± standard error of the mean (bars). Different letters indicate significant statistical difference between dates (March to September (**a**,**b**); 2010 to 2017 (**c**,**d**)) in the same plots and asterisks between K fertilization levels (K250 to K0) at the same date according to Student's *t*-test ($p \leq 0.05$).

Soil exchangeable K in the soil profile did not differ significantly prior to the beginning of the experiment (2010; Figure 1c). However, following six consecutive seasons (2017), the exchangeable K content in the two upper soil layers (0–30 and 30–60 cm) of plots that were fertilized with K increased significantly compared to the beginning of the experiment (Figure 1c,d). The continuous K fertilization led to the enrichment of the soil exchangeable K pool.

3.2. Leaf and Fruit Minerals Concentration

No substantial differences were eminent in diagnostic leaf macro-element (N, P, K) concentrations at the initiation of the experiment (July 2011; Figure 2a–c). During the duration of the experiment, leaf

N, P, and K concentrations all generally increased, including K concentrations in trees growing without K fertilization (K0; Figure 2a–c). Following two seasons of treatment application (July 2013), leaf K consentrations were higher in trees fertilized with K relative to the K0 treatment (Figure 2c). In the following seasons (2014–2015), the leaf K concentration in the K250 trees continued to increase relative to K0 (Figure 2c). Leaf P and N concentrations were not significantly affected by the K fertilization, except for N in the 2015 season, where concentrations in the K0 treatment were somewhat higher (Figure 2a,b). Contrary to this, leaf Na concentrations were higher in the K0 treatment during 2014–2015 seasons (Figure 2d).

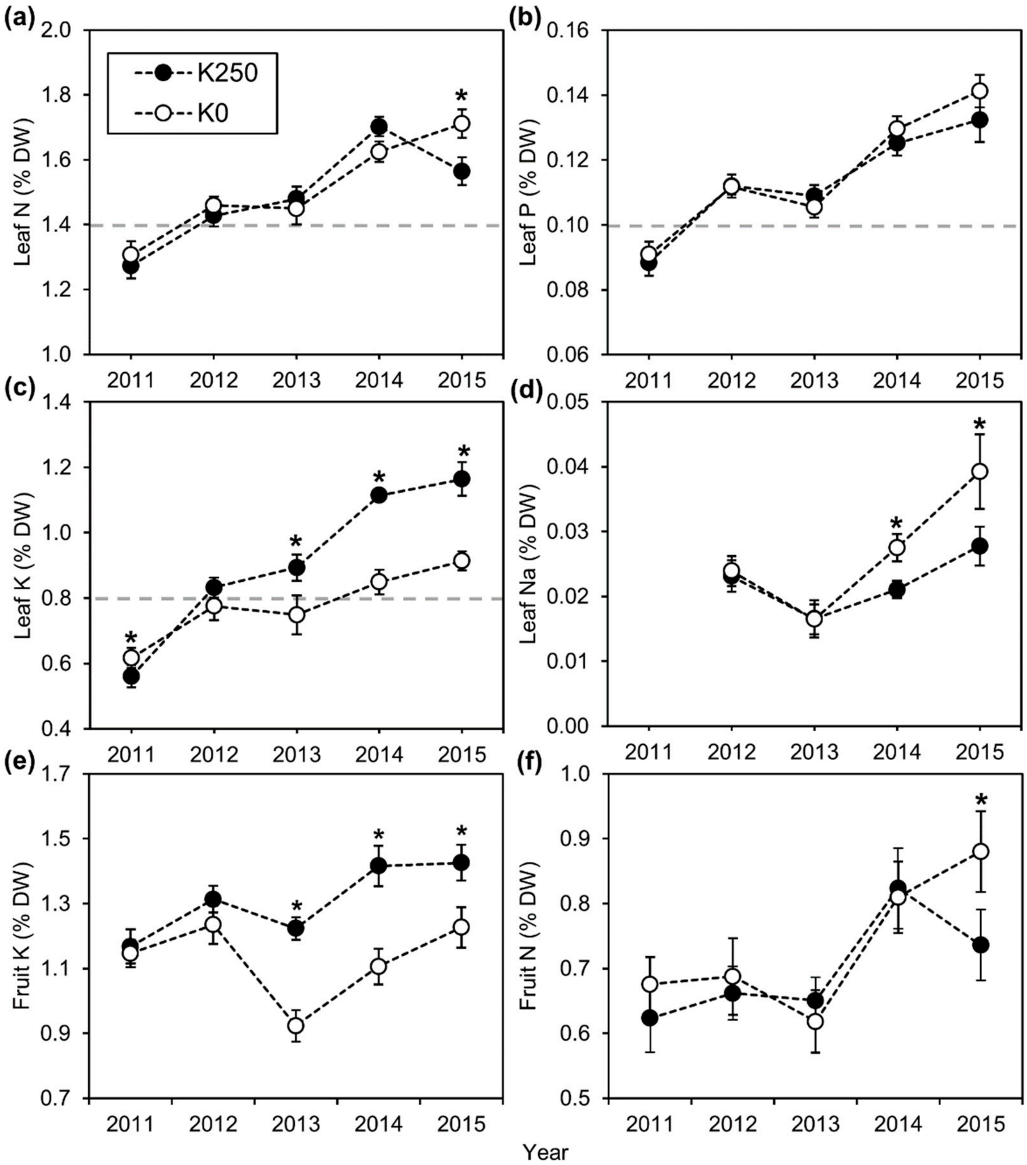

Figure 2. Influence of K fertilization on leaf and fruit mineral concentrations. Experimental plots were fertilized either with an annual amount of 250 kg K ha^{-1} (K250) or without K (K0). Leaf N (**a**), P (**b**), K (**c**), and Na (**d**) concentrations were determined in diagnostic leaves sampled during July as percentage form dry weight (DW). Fruit K (**e**) and N (**f**) concentrations were determined in a sample of fruits at harvest. Numbers are mean values of 14 replicates (trees) ± standard error of the mean (bars). The dashed grey lines show the deficiency-sufficiency threshold for the specific mineral. Asterisks indicate significant statistical difference between K fertilization levels in the specified date according to Student's *t*-test ($p \leq 0.05$). Values of leaf N for K250 were published previously [33].

As found for leaves, fruit K concentration was not affected by K fertilization during the first two seasons (Figure 2e). In the following seasons, fruit from the K250 treatment accumulated significantly more K (Figure 2e). Fruit N concentration was not significantly affected, except in the 2015 season, where both fruit and leaf N concentrations were slightly higher in trees from K0 treatment (Figure 2a,f).

3.3. Vegetative Growth

The relative increase in tree trunk circumference was not significantly different after six consecutive years of differential fertilization (Table 1). Similarly, the mean pruning material weight following the 2012–2015 seasons was also not affected by the fertilization regime (Table 1). Hence, the K availability did not influence vegetative development over the six seasons of the experiment.

Table 1. Influence of K fertilization on vegetative and reproductive development.

Annual K Fertilization	Trunk Circumference Increase	Pruning Weight	Flowering Intensity	Inflorescences Initiation [a]
	2011–2017	2012–2015	2014–2017	2014–2015
(kg ha^{-1})	(%)	(kg tree^{-1})	(index)	(%)
0	71.8 ± 2.7 a	36.6 ± 3.0 a	3.00 ± 0.15 b	35.4 ± 1.8 b
250 [b]	74.3 ± 2.8 a	34.0 ± 2.5 a	3.34 ± 0.11 a	44.5 ± 3.2 a

Numbers are mean values of 14 replicates (trees) ± standard error of the mean. Different letters indicate statistically significant differences according to Student's *t*-test ($p \leq 0.05$). [a] The rate of buds which initiated an inflorescence. [b] Values of this level were published previously [33].

3.4. Flowering and Fruit Set

In contrast to vegetative development, reproductive development was significantly affected by K fertilization. In both the visual estimation of flowering and the measured rate of inflorescence initiation, flowering intensity was lower in the K0 treatment (Table 1). Flowering quality traits, such as the number of flowers in an inflorescence, percent of perfect flowers, and the flower pistil weight were not affected (Table 2). However, the rate of fruit set was significantly lower in the K0 trees (Table 2).

Table 2. Influence of K fertilization on flowering quality traits and fruit set.

Annual K Fertilization	Flowers in an Inflorescence	Perfect Flowers	Pistil Weight	Fruit Set
(kg ha^{-1})	(No.)	(%)	(mg)	(%)
0	16.1 ± 0.6 a	56.5 ± 2.9 a	0.72 ± 0.03 a	5.2 ± 0.4 b
250 [a]	16.2 ± 0.5 a	56.5 ± 3.3 a	0.79 ± 0.04 a	6.7 ± 0.6 a

Trees flowered at medium to high intensities (index of 3–5) in seasons 2014–2017. Numbers are mean values of 22–28 replicates (trees) ± standard error of the mean. Different letters indicate statistically significant difference according to Student's t-test ($p \leq 0.05$). [a] Values of this level were published previously [33].

3.5. Yields

The cumulative, six-year fruit yield of trees receiving no K fertilizer was significantly lower (Figure 3), producing on average 20% less fruit in the 2013–2016 seasons compared to the K fertilized trees (Table 3). Fruit oil content did not fluctuate much, and thus, estimated oil yields were similarly significantly lower in the K0 trees (Table 3). The mean weight of a single fruit was not affected, and therefore, the estimated number of fruits produced per tree was significantly higher in the K fertilized trees (Table 3). Seasonal fruit yield data is presented as supplementary material (Table S2).

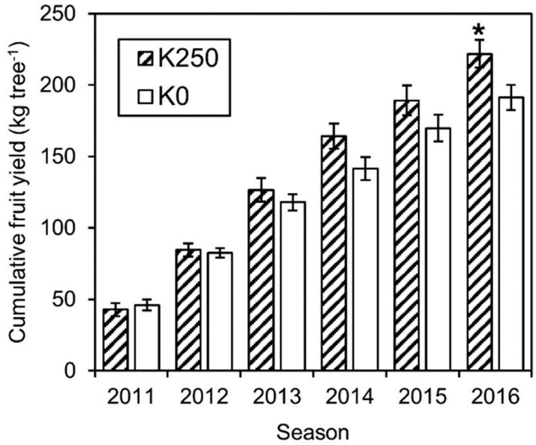

Figure 3. Influence of K fertilization on cumulative fruit yield. Experiment plots were fertilized either with an annual amount of 250 kg K ha^{-1} (K250) or without K (K0). Cumulative fruit yield per tree over six seasons, from 2011 until 2016. Numbers are mean values of 14 replicates (trees) ± standard error of the mean (bars). Asterisks indicate statistically significant difference between K fertilization levels according to Student's *t*-test ($p \leq 0.05$).

Table 3. Implications of K fertilization on yields.

Annual K Fertilization	Single Fruit Weight	Oil Content	Annual Number of Fruits Per Tree	Annual Fruit Yield	Annual Oil Yield
	2013–2016	**2013–2016**	**2013–2016**	**2013–2016**	**2013–2016**
(kg ha^{-1})	(g)	(% DW)	(No. $tree^{-1}$)	(kg $tree^{-1}$)	(kg $tree^{-1}$)
0	2.37 ± 0.08 a	18.9 ± 0.5 a	15,962 ± 1738 b	27.3 ± 1.9 b	4.5 ± 0.3 b
250 [a]	2.42 ± 0.09 a	19.6 ± 0.6 a	19,813 ± 1141 a	34.0 ± 1.6 a	5.6 ± 0.4 a

Numbers are mean values of 14 replicates (trees) ± standard error of the mean. Different letters indicate statistically significant difference according to Student's t-test ($p \leq 0.05$). [a] Values of this level were published previously [33].

3.6. Alternate Bearing

The calculated index for the alternate bearing intensity of the trees growing without K fertilization was significantly higher compared to the fertilized trees (Table 4). In addition, following seasons with medium to high fruit loads (20–70 kg $tree^{-1}$), flowering intensity was significantly reduced in trees growing without K fertilization, with an average flowering score of 1.7 compared to 2.9 in the K fertilized trees (Table 4).

Table 4. Influence of K fertilization on alternate bearing.

Annual K Fertilization	Alternate Bearing Intensity [a]	Flowering Intensity [b]	Fruit Yield [c]
(kg ha^{-1})	(index)	(index)	(kg $tree^{-1}$)
0	0.72 ± 0.04 a	1.7 ± 0.35 b	46.1 ± 3.0 a
250	0.53 ± 0.08 b	2.9 ± 0.25 a	44.0 ± 2.3 a

Numbers are mean values ± standard error of the mean. Different letters indicate statistically significant difference according to Student's t-test ($p \leq 0.05$). [a] Calculated for 2012–2016 seasons according to Monselise and Goldschmidt [32]. N = 11–14 (trees). [b] Of trees that bore in the previous season a medium to high fruit load (20–70 kg $tree^{-1}$ in 2013–2016 seasons). The mean fruit yield of these trees in the previous season is presented in the next column ([c]). n = 23–33 (trees).

4. Discussion

4.1. Soil K Content

Analysis of saturated soil paste extract enables estimation of K immediately available for uptake by plant roots [7]. Thus, the lower levels of soil saturated paste K content in the plots receiving no K fertilizer indicated reduced availability of K to the trees. In both fertilization regimes and all depths, soil solution K levels were significantly higher at the end of the irrigation seasons compared to the beginning of the seasons (Figure 1a,b). As this is also true for plots where K fertilization was omitted, the higher levels at the end of the irrigation seasons cannot be attributed exclusively to the K fertilization. Possibly, the lower K levels following winter (at spring) were the result of K leaching by winter precipitation. Erel et al. [28] observed a similar trend in a long-term experiment evaluating the effect of reclaimed wastewater on soil properties. Moreover, the higher K levels at the end of the irrigation seasons in the K0 treatment may be due to K originating in the irrigation water (19 kg K ha^{-1} $season^{-1}$).

The higher concentrations of K in the soil solution under K fertigation increased K levels in the exchangeable K pool throughout the duration of the experiment (Figure 1d). In the long-run, increasing values of exchangeable potassium percentage (EPP) from the soil cation exchange capacity (CEC) can impair soil hydraulic conductivity and infiltration rate, leading to soil erodibility [34,35]. However, the highest EPP value calculated with the exchangeable K (Figure 1d) and soil CEC (Table S1) values at the time of concluding the experiment was 3.6%, which is moderate and not expected to accelerate soil dispersion. That said, the continued increase in EPP presents a risk of soil degradation in subsequent years and should be considered and monitored.

Conversely, K depletion in the K0 plots soil led to considerable depletion of exchangeable K from 6.5 to 4.5 meq kg^{-1} in the upper soil layer (Figure 1c,d). This depletion is expected to increase the free energy of K sorption in the exchangeable phase, a term often expressed as ΔF [36]. In this case, ΔF at the beginning of the experiment (April 2011) was similar among the experiment treatments (Table 5). After six seasons (March 2017) ΔF decreased to −3888 in the K0 treatment, while in the K250 treatment, the ΔF value increased to −3328 (Table 5). The accepted threshold in Israel for K deficiency is ΔF < −3500 [37]. The ΔF in the K0 treatment is an indication that the K availability in that soil was considerably low.

Table 5. The long-term effect of K fertilization on ΔF.

	Date:			
	Prior to the Initiation of the Experiment (April 2011)		**Following Six Seasons of Differential Fertilization (March 2017)**	
	Annual K fertilization (kg ha^{-1})			
	K0	K250	K0	K250
Soil layer (cm)	ΔF (cal mol^{-1} K)			
0–30	−3387 ± 91 a	−3176 ± 114 a	−3894 ± 43 b	−3074 ± 167 a
30–60	−3598 ± 63 a	−3594 ± 110 a	−3914 ± 47 b	−3412 ± 183 a
60–90	−3673 ± 91 a	−3759 ± 67 a	−3856 ± 31 b	−3499 ± 166 a
0–90 [a]	−3552 ± 47 a	−3510 ± 77 a	−3888 ± 23 b	−3328 ± 103 a

Numbers are mean values of seven sampling locations (plots) ± standard error of the mean. Different letters indicate statistically significant differences between K fertilization levels (K0 to K250) in the specific date and soil layer according to Student's t-test ($p \leq 0.05$). [a] Average of all three soil layers (0–30, 30–60, and 60–90 cm).

4.2. Potassium Offset

The changes in soil exchangeable K by fertilization on one hand, and the offtake by fruit yield on the other, allow us to roughly estimate the K offsets in the orchard. Throughout the experiment, the average K depletion from the soil exchangeable pool across the soil layers in the K0 treatment was 45 kg ha^{-1} season^{-1} (Table 6). In the K250 treatment, exchangeable K accumulated across the soil layers at an average annual rate of 105 kg ha^{-1} (Table 6).

Table 6. Changes in soil exchangeable K as a function of K fertilization.

	Change in Soil Exchangeable K (2010 to 2017) [a]			
	K0		K250	
Soil layer (cm)	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}
0–30	−75.3	−140.3	202.4	377.4
30–60	−41.3	−77.1	114.3	213.0
60–90	−28.1	−52.3	21.1	39.3
0–90 [b]		−269.7		629.6
Per season [c]		−45.0		104.9

[a] Calculated with the soil exchangeable K values presented in Figure 1c,d. [b] Sum of the three soil layers (0–30, 30–60 and 60–90 cm). [c] The sum of the three soil layers divided by six (for the six seasons of implementing the experiment treatments).

Potassium offtake from the orchards by fruit yield during the experiment years was significantly higher in K250: an average of 85 kg ha^{-1} season^{-1} compared to 63 in K0 (Table S2). For the K0 treatment, this (63 kg ha^{-1} season $^{-1}$) was equivalent to the 62 kg ha^{-1} total annual K supplied by the irrigation water (19 kg ha^{-1}) plus that supplied from the exchangeable pool (45 kg ha^{-1}). For K250, annual K input was 269 kg ha^{-1} (250 kg fertilized + 19 kg from the water), while K offtake by fruit yield was 85 kg ha^{-1} season^{-1} and the exchangeable K accumulated in the soil profile was 105 kg ha^{-1} season^{-1}. The sum of K offtake by fruit yield and the deposit into the exchangeable pool does not add up to the applied amount of K (190 compared to 269 kg ha^{-1} season^{-1}), leaving 79 kg of "missing" K in the balance (Table 7). This significant amount of K may have been leached due to the excessive K application rate, or simply be a result of undetermined parameters (e.g., K storage in the tree).

Table 7. Potassium balance.

	Annual K Fertilization (kg ha^{-1})	
	K0	K250
Potassium Source	Potassium Input/Offtake (kg ha^{-1} season^{-1})	
Irrigation water	19	19
Fertilizer	0	250
Fruit yield	−63	−85
Exchangeable K [a]	+45	−105
Balance	1	79

[a] Calculated in Table 6.

In the current experiment, the K0 treatment clearly led to soil K depletion and impaired soil productivity, while the K250 treatment affected significant soil K accumulation, and potentially, K losses. Hence, the optimal K dose for the experimental orchard was probably between 0 and 250 kg ha^{-1} season^{-1}. Considering the combined soil and plant measurements, we carefully suggest that, to avoid accumulation or depletion of soil exchangeable K levels at high yields, orchard K requirement where the experiment was conducted was 164 kg ha^{-1} season^{-1} (269 kg (applied) − 105 kg (deposition to the soil)).

4.3. Leaf and Fruit Mineral Concentration

Following two seasons of differential fertilization, leaf K concentration in trees growing in the K fertilized plots increased and were significantly higher than in non-K fertilized trees (Figure 2c). Thus, higher K availability in the soil supported a higher intake of K by tree roots. During the experiment, leaf K concentrations somewhat increased in trees growing without K fertilization as well (Figure 2c). Zipori et al. [25] demonstrated that K nutritional status of olive trees can be influenced by irrigation rate. Thus, the increase in leaf K in the K0 treatment may be attributed to the proper irrigation implemented during the experiment, facilitating the migration of K from the exchangeable K pool to the soil solution and resulting in increased K availability to the trees. The exchangeable K levels in plots not fertilized with K were indeed somewhat lower at the end of the experiment (Figure 1c,d).

The average K concentration in diagnostic leaves from trees growing without K fertilization in the 2014–2015 seasons was 0.88%, just above the generally accepted sufficiency threshold of 0.80% [10]. Still, these trees had impaired productivity compared to the K fertilized trees and would have likely benefited from higher K availability. Therefore, it can be postulated that the trees were indeed K deficient. This suggests that the K sufficiency threshold for olives in irrigated intensive orchards should be higher than commonly acknowledged. Previous studies on olive K fertilization were mainly conducted in rain-fed orchards in which water could be expected to limit productivity and where requirements for K were, therefore, relatively low. Additionally, in intensive systems, the K offtake is significantly higher due to substantial increases in yield.

Along with K, Na concentrations in diagnostic leaves were also affected by K fertilization (Figure 2d). This is not surprising, as Na is suggested to replace K in physiological processes in olive when K availability is reduced [38]. The increased uptake of Na is an additional indication for the deficit in K uptake.

4.4. Vegetative and Reproductive Development

In the six-year time-span of our experiment, low K availability did not appear to have a significant effect on olive tree vegetative growth. In contrast, K availability had significant affected tree reproductive development as, under the lower K availability, flowering and fruit set rates were significantly lower, resulting in a reduced amount of fruit. Previous studies on olive mineral nutrition, using container-grown olive trees, reported that K availability had only a marginal effect on tree performance, especially when compared to the effect of N and P [22–24]. Erel et al. [23] observed a significant reduction in the reproductive development of the container-grown trees only when leaf K concentrations decreased below 0.3%. A possible explanation for the marginal effect in container-grown trees may be due to very high and constant water availability supplied to the trees in such experiments.

Hypothetically, productivity may be regulated according to combined tree fitness and the resources available to support fruit development. Thus, differences in flowering and fruit set in our case were perhaps driven in some way by tree physiological fitness, as affected by K nutritional status. A tree's carbohydrate budget is often suggested to be a central component in the regulation of productivity [39,40]. Potassium was demonstrated to be important for CO_2 assimilation and general photosynthetic capacity of olive trees [38,41]. In addition, starch levels were found higher in olive trees growing under higher K availability [38]. Perhaps the down-regulation of reproductive development, induced here by lower K availability, is the outcome of lower photosynthetic capacity.

4.5. Alternate Bearing

The stability of yields between seasons is important to olive growers. Olives have a high tendency to alternate bearing, which results in yield fluctuation [42]. Olive alternate bearing is driven by the inhibitory effect of high fruit load on tree growth and flowering [43,44]. Thus, higher flowering intensity following fruit-bearing is a desirable trait. In the current study, trees receiving no K fertilizer had a higher alternate bearing index and flowered at significantly lower intensities following seasons with medium to high fruit loads (Table 4) and thus appeared to have more significant alternate bearing cycles. Similar phenomena were found in olive and avocado (*Persea americana* Mill.) for N fertilization [33,45].

Olive fruit are a substantial sink for K, and therefore, after an 'On' year K reserves may be depleted [14,16]. More than any other nutrient, K concentrations in olive tree leaves, bark, and roots are influenced by the fruit load [16,46]. This effect of fruit load on the tree K levels may maintain and amplify the yield fluctuations of alternate bearing.

5. Conclusions

Potassium fertilization supported higher and more stable long-term yields of olives. Omitting K fertilization for over three years resulted in a substantial decrease in yield, attributed to down-regulation of tree reproductive development but not vegetative growth. Regular K fertilization should be integrated into the management of intensively cultivated olive orchards, even when trees do not show symptoms of K deficiency, as 'hidden hunger' cannot be visually identified. Potassium fertilizer in Israel costs about \$1.7 Kg^{-1} K_2O [47]. Assuming an annual application level of 250 kg K ha^{-1}, this price level translates to annual spending of \$350 ha^{-1}. In the third to the sixth season of the experiment, the annual increase in yield in the K250 treatment was 396 kg ha^{-1} (calculated with the data in Table 3). Given that the price of olive oil ranges around \$4 [48], this increase is equal to ~\$1,584 annually, justifying the spending on the K fertilizer.

Even though K concentrations in diagnostic leaves from trees in the K0 treatment were within levels commonly assumed to be sufficient, yields were significantly reduced. The recommended thresholds for proper K concentrations in diagnostic leaves should, therefore, be reconsidered for intensive irrigated olive cultivation. In addition, the fertilizer dose may be better determined using values of available K in the soil. Obtaining a reliable diagnosis of the orchard (trees and soil) K nutritional status and the deduction of the proper fertilization amount are challenging, as they are influenced by several parameters. We speculate that in the upcoming future of intensive and precision agriculture, leaf K and Na concentrations combined with trends in soil exchangeable K and the calculation of energy for K sorption (ΔF) will be integrated into the diagnosis of K nutritional status and the deduction of proper fertilization.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/9/9/525/s1, **Figure S1**: Meteorological data, **Table S1**: Soil physical and chemical properties, **Table S2**: Seasonal fruit yields and fruit K offsets.

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