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Root Asphyxia and Irrigation Management in Avocado Orchards

Introduction

Yields in avocado orchards (Persea americana Mill.) are lower than in other fruit crops (Wolstenholme, 1986). This is due to the high cost of energy required to produce large-seeded fruit, rich in oil. It has been observed in 'Hass' avocado orchards planted in the central zone of Chile, that under favorable growing conditions, yields can be maintained at over 22 ton/ha as compared to the national average of 9 tons/ha. One of the reasons for low yields in avocado groves in Chile is that many orchards are planted in soils with physical properties (texture, structure and air capacity) that are unfavorable for avocado root development. The products of photosynthesis and the entire nutrient reserves of trees are distributed preferentially to the fruit and the vegetative growth at the expense of the root system (Cannell, 1985), making the roots highly susceptible to asphyxia, especially in soils with high bulk densities, high water retention and low air capacity. The susceptibility to asphyxia is aggravated if the orchards are watered improperly.

In soils such as those found in the central zone of Chile, the avocado trees have shallow roots and are planted in soils with low hydraulic conductivity leading to poor root growth due to anoxia and decreased water uptake. Poor root growth results in low water and nutrient use efficiency that limits photosynthesis. When root growth is poor, water uptake will be impaired and will result in leaf water stress leading to stomatal closure. This shuts off gas exchange leading to cessation of photosynthesis and decreased production of carbon products (sugars, fatty acids, proteins) that are required for good tree growth and high fruit yields.

The shallow root growth habit of avocado is probably due to the fact that the avocado evolved in very favorable soil conditions that are very different from the heavier soils which are found in the commercial growing areas of Chile.

When there is an oxygen deficient period, whether for a short or long duration, it results in the inhibition of root growth, causing necrosis and inhibition of shoot growth followed by moderate to severe leaf abscission (Stolzy et al., 1967; Schaffer et al., 1992). The avocado's center of origin is in the highlands of Mexico and Guatemala where it evolved on Andisol soils. This type of soil is derived from volcanic ash, it is characterized by low bulk densities (0.5 to 0.8 g/cm3), high air capacity (air capacity corresponds to the number of pores with air in a soil at field capacity), high organic matter content, acidic pH and rapid drainage (Aguilera et al., 1991). [Bulk densities of avocado soils in California for example range from 1.2 – 1.6 g/cm3 (D. Crowley, personal communication) Eds.]).

The avocado grows well in soils with an air capacity of about 30% (Ferreyra et al., 2007a). The trees begin to show symptoms of root asphyxia with the soil air drops to around 17% (Figures 1-5). On the other hand, Gil (2008) found that even in non-asphyxia well aerated conditions, a high water-to-air ratio has a negative effect on the avocado plant's physiology, which at the end is expressed as a lower biomass, indicating the high sensitivity of this species to lack of aeration (Figure 6).

Figure 1. Two-year old 'Hass' avocado on seedling 'Mexicola' rootstock growing in 29% soil air content.

Figure 2. Two-year old 'Hass' avocado on seedling 'Mexicola' rootstock growing in 7% soil air content.

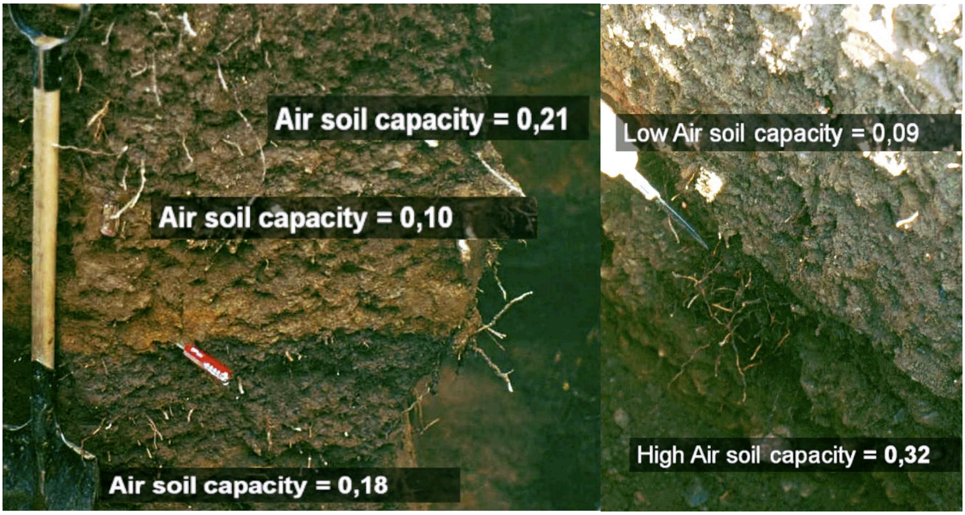

Figure 3. Soil air capacity and root growth (photo by R. Ruiz).

Figure 4. 'Hass' avocados on seedling 'Mexicola' rootstock growing in soil with high air capacity (27%). Orchards without root asphyxia have sustained average yield of 25 ton/ ha.

Figure 5. 'Hass' avocado on seedling 'Mexicola' rootstock growing in soil with low air capacity (12%). Orchards with root asphyxia have sustained average yield of 8 ton/ha.

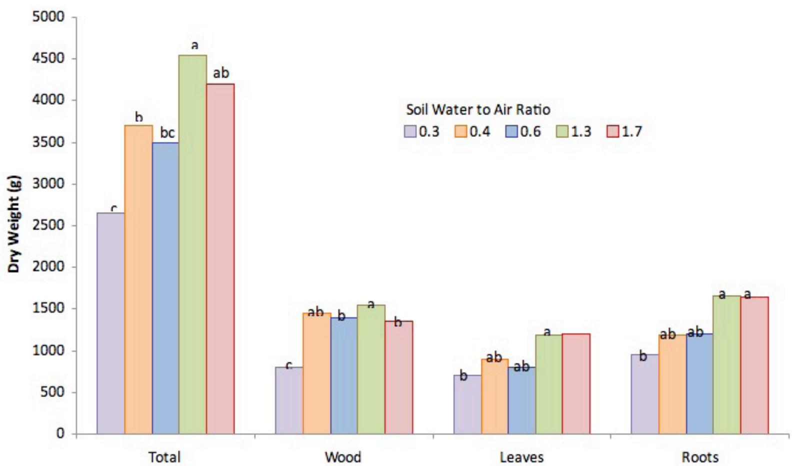

Figure 6. Dry weight of 'Hass' avocado tissue, grown on seedling 'Mexicola' rootstock. Bars indicate means of 4 replicates. Different letters (a, b, c) indicate significant differences (Waller – Duncan Test. P ≤ 0.1). Treatments correspond to soil water-to-air ratio (W/A). W/A were 0.3, 0.4, 0.6, 1.3 and 1.y.

Soil aeration effects on crop development

Lack of oxygen in the soil induces multiple physiological disorders in plants such as stomatal closure, reduced root growth (Lafitte, 2001), and consequently, inhibition of photosynthesis and transport of carbohydrates (Kozlowski, 1997). It also reduces the absorption of macronutrients, because of root mortality, loss of mycorrhizae, and a malfunction of root metabolism (Kozlowski, 1997). It has been found that low oxygen concentration in the soil alters the hormonal balance in the plant including increased ethylene synthesis (Kozlowski, 1997) accumulation of abscisic acid and auxins such as (IAA), and a reduction of cytokinins and gibberellic acid levels (Lafitte, 2001). There is also damage to the root system due to the accumulation of ethylene and other toxic products as a result of anaerobic respiration. [A good review on the impact of soil aeration on photosynthesis is Sojka et al. (2005).]

Excess moisture in the soil displaces the air from the pore spaces, decreasing the concentration and diffusion rate of oxygen (O2), which leads to a reduction of root aerobic respiration. With the reduction of oxygen in the soil there is an increase in the levels of carbon dioxide (CO2) leading to an anaerobic decomposition of organic matter, in which iron and manganese pass to their reduced forms (Kozlowski, 1997). The avocado develops well in soils containing 15% oxygen and 0.03% carbon dioxide (Menge and Marais, 2000). Stolzy et al. (1967) report that 'Mexicola' avocado plants, growing in soils with an oxygen diffusion rate less than 0.17 µg cm-2 min-1 have about 44% to 100% of their root systems damaged. On the other hand, other cultivars such as 'Scott', 'Duke' and 'Topa Topa', do not grow when the oxygen diffusion rate is less than 0.20 µg cm-2 min-1 (Valoras et al., 1964). Loamy soil, with frequent irrigation (daily watering) and high water content, may have oxygen diffusion rates under the limit reported above (Figure 7). The oxygen diffusion rate is closely related to soil pore space occupied by air. Ferreyra et al. (2007a), found that the oxygen diffusion rate (ODR) was more than 80% higher in soils with 29.87% air (T1 sandy soil) as compared to a loamy soil with air content below 17% (Figure 7), where the ODR is less than 0.2 µg cm-2 min-1.

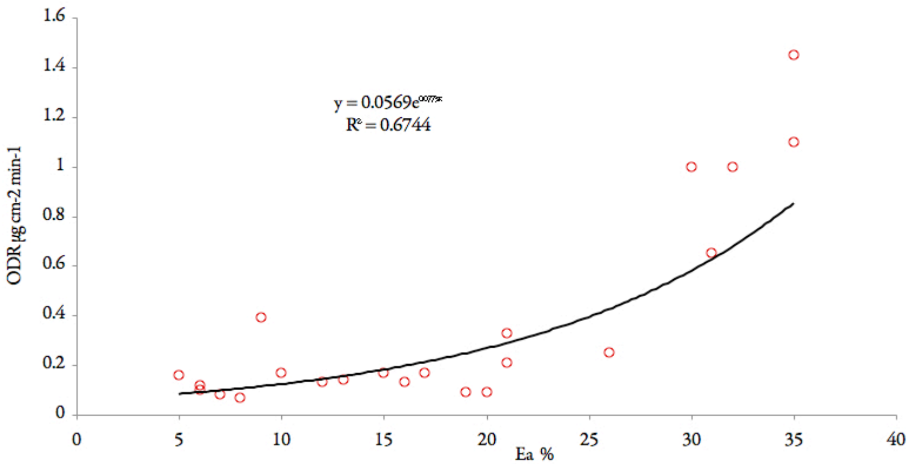

Figure 7. Relationship between oxygen diffusion rate (ODR) and soil air volume (Ea) in soils managed with frequent irrigation and high moisture content.

In most plant species, the air content in the root zone needs to be more than 10% of the total soil volume (Sellés et al., 2003), however, for avocado roots to develop well the appropriate threshold is about 30% (Ferreyra et al., 2008). Therefore, planting in fine textured or poorly structured soils, with poor irrigation management, can lead to problems with root development, vegetative growth and plant water status (Tables 1 and 2).

Table 1. The effect of air content in soil (Ea) on the leaf area index (LAI) of 'Hass' avocado on seedling 'Mexicola' rootstock.

Treatment	Ea (%)	LAI (m^2)
T0	7.46	1.58 a
T1	29.08	4.40 b
T2	20.44	2.44 a
T3	14.36	2.55 a

Different letters indicate significant difference according to the multiple comparison test of Tukey (P = 0.05).

Table 2. Effect of soil air content (Ea) on stomatal conductance (gs) measured at midday (14:00 hrs) as influenced by vegetative vigor.

Vegetative Vigor	Treatment							
	T0		T1		T2		T3	
	gs (cm s^{-1})	Ea (%)	gs (cm s^{-1})	Ea (%)	gs (cm s^{-1})	Ea (%)	gs (cm s^{-1})	Ea (%)
Low	0.12 a	7.48	0.29 b	28.02	0.19 a	22.59	0.15 a	12.24
High	0.26 a	7.28	0.56 b	29.98	0.30 a	21.29	0.34 a	16.23
Average	0.19	7.38	0.43	29.00	0.24	21.94	0.25	14.24

Different letters indicate significant difference according to the multiple comparison test of Tukey (P = 0.05). T0 = 7.46 % Ea T1 =; 29.08% Ea; T2= 20.44%Ea; T3=14.36%Ea.

The data presented in Tables 1 and 2 indicate that for proper root and vegetative development of avocado trees it is necessary to maintain an appropriate water-to-air balance in the soil. This simple idea is difficult to implement, especially in fine textured soils, because the water content increases and aeration decreases significantly with every irrigation. The larger diameter pores drain slowly until moisture levels near field capacity are reached. Therefore, an irrigation program for avocados needs to take a holistic approach. It is not sufficient just to consider the water requirements but also the soil physical conditions including the interaction between aeration, moisture retention and soil mechanical resistance (Figure 8).

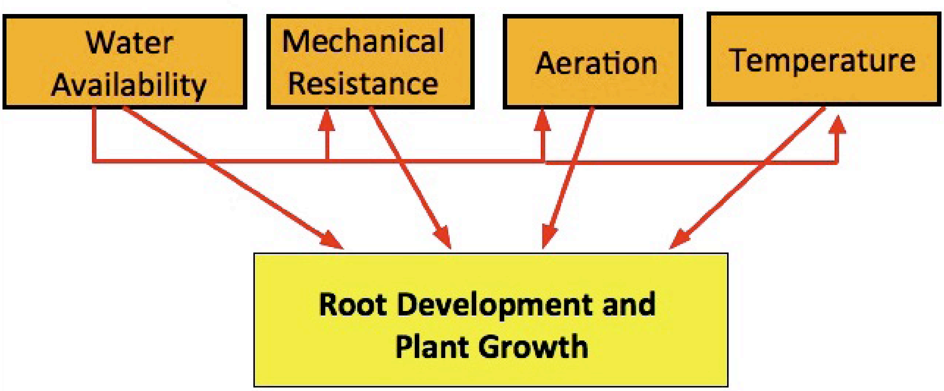

Figure 8. Soil factors that affect root and aerial development of plants. .

Root asphyxia symptoms

Short periods of low soil oxygen content usually lead to decrease and/or death of the root system. This may affect shoot growth, inhibit leaf expansion, cause moderate to severe leaf abscission (Stolzy et al., 1967; Schaffer et al., 1992) and also cause leaf tip burn (Valoras, 1964). Root asphyxia symptoms vary in magnitude depending on the soil air content. Figures 9 through 17 illustrate typical symptoms of root asphyxia.

Figure 9. 'Hass' avocado on seedling 'Mexicola' rootstock with normal growth.

Figure 10. Symptoms of root asphyxia: Few roots of poor quality.

Figure 11. Symptoms of root asphyxia in 'Hass' avocado on seedling 'Mexicola' rootstock: Defoliated trees with small and narrow leaves. These are not trees affected by avocado root rot, *Phytophthora cinnamomi*.

Figure 12. Symptoms of root asphyxia: Abundant leaf drop during bloom.

Figure 13. Symptoms of root asphyxia: Unusually high fruit drop in late spring and / or summer.

Figure 14. Symptoms of root asphyxia of 'Hass' avocado on seedling 'Mexicola' rootstock: Defoliation of vegetative spring shoots; fruit and wood are candidates for sunburn.

Figure 15. Symptoms of root asphyxia: Defoliated trees, excessive flowering in orchards with high water accumulation.

Figure 16. Symptoms of root asphyxia: Defoliated trees, small fruits, narrow yellow-green leaves.

Figure 17. Symptoms of root asphyxia: Trees with tip burned leaves (these symptoms are not due to high salinity or chloride accumulation in the leaves).

Causes for poor soil aeration

The main cause for poor soil aeration is linked to the soil physical properties, such as texture, structure and bulk density. Fine texture, poor structure and high bulk density reduce the air capacity of the soil and therefore root oxygenation. Poor soil structure due to low soil organic matter content (OM) can also contribute to soil aeration problems. OM improves soil aggregate stability and the formation of macro aggregates that allow macropores to form in the soil. OM also promotes earthworm activity leading to macropores that can drain the soil and allow introduction of oxygen. Aeration problems may be worsened by incorrect irrigation practices, whether related to irrigation equipment or water management.

Some typical circumstances leading to root asphyxia in avocado orchards are discussed below. Generally more than one of these causes may be present in orchards with trees that show some degree of root asphyxia.

a. Lack of consideration for the natural rainwater drainage channels in the orchard. This results in winter rain draining slowly from the orchard and some areas unfortunately end up with trees that have root asphyxia. This is common in flat areas below the planted slope.
b. In orchards with low soil air capacity, initiating irrigation while there is still high water content in the soil.
c. Excessive irrigation in soils with poor drainage.
d. Uneven discharge among emitters. When irrigation equipment has uneven flow in drip emitters or sprinklers, the amount of water delivered by some emitters can differ from others by 2 to 3 times in the same irrigation line. The uneven flow is caused by several factors such as emitter blockage, existence of emitters with different output in the same line, un-calibrated valves and low water pressure.
e. Irrigation excess at the end of the rows when the orchard is on a slope and the lines are laid parallel to the slope. When the water is turned off, water is discharged at the end of the rows at the bottom of a block or the orchard. This commonly occurs when irrigation systems do not have auto-compensated or anti-drainage emitters.
f. Poor irrigation uniformity. This problem may be due to low percentage of soil area wetted by emitters, the use of a microsprinkler models with an uneven wetting pattern and/or low branches interfering with the microsprinkler watering pattern.
g. Irrigation blocks not designed according to homogeneous types of soil texture, depth or topography.

In order to control root asphyxia it is necessary to determine the existence of low soil aeration in the orchard, and then analyze the cause of the problem and decide on corrective measures. The use of rootstocks with tolerance to low soil aeration is another way to address root asphyxia. However, currently there is no information that indicates how different rootstocks perform under this condition because in most cases avocado rootstocks have been selected for other aspects such as Phytophthora root rot or salinity tolerance.

Irrigation water management strategies to optimize the water-to-air ratio in the root zone

When drip and low volume sprinkler technology was first introduced along with the concept of water replacement based on crop evapotranspiration (ETc), it was believed that irrigation should take place on a daily basis. Currently, experience has shown that high frequency irrigation is more appropriate for soils with low water holding capacity, with medium to coarse texture and with high air capacity. In heavier soils with higher moisture retention capacity and low air capacity, the low frequency irrigation (irrigation every 2, 3 or more days in summer) is more desirable. The daily water applications in clays and silty loam soils (soils with low air capacity) may cause problems due to lack of oxygen in the soil.

Traditionally, the strategy for daily irrigation has been to keep the soil water content near field capacity by replenishing the daily ETc. Daily watering is a valid strategy but the soil physical properties need to be considered. For instance, daily irrigation can be applied even in fine textured soils, but it should be initiated with soil water content lower than in sandy soil. The timing of irrigation needs to take into consideration how much water is held in the soil since this can make a difference from the soil aeration point of view. As shown in Figure 18 (light blue line), when loamy soil (soil porosity of 50%) is irrigated with 30% water content and 20% air capacity the soil is under field capacity. If the soil is watered daily with that condition, the water content of the soil will be kept above field capacity (FC line, Figure 18), and thus, the air content in the soil will be below 17% (secondary Y axis). However, the situation will be totally different if daily irrigation begins when the soil has low water content; lower than at field capacity (green line, Figure 18). For example, when irrigation begins with a soil water content of 25%, which means watering the plants when 30 to 40% of the available moisture has already been depleted, the soil air content can be maintained at 25% (green line, Figure 18). Therefore, when using the strategy of daily watering it is essential to know the soil's field capacity and its air capacity to properly define the time (or water content) that the soil should have at the beginning of the irrigation period. This will allow the grower to replace the daily ETc as well as maintain adequate air and water content in the soil. It is necessary to consider these factors when developing an irrigation management strategy especially in soils that are not ideal for avocado because under these conditions irrigation management requires strict control of soil moisture and plant water status; any mistake can seriously affect the development, production and sustainability of the crop.

Another way to replace water while optimizing the air-water relation in the soil is through low-frequency irrigation. Under this technique water is depleted by about 40% of the soil available moisture, a level that does not affect avocado growth and productivity. Using this strategy there is a period of drainage and aeration between each watering event, increasing the amount and distribution of oxygen in the soil (red line, Figure 18). The amount of water applied at each irrigation interval corresponds to the cumulative amount of water, taken from daily evapotranspiration during that period. Thus, the amount of water applied in low frequency irrigation is the same as that applied in daily watering, changing only the application frequency. The low-frequency technique is a simple and safe way to implement and allows leaching of sodium/chloride salts, when salinity is a factor limiting avocado production.

Defining the most appropriate irrigation frequency for a given soil type is necessary to achieve good production, fruit quality and fruit size. It is important to optimize the water-to-air ratio in the soil to avoid causing any physiological stress to the trees. To define a proper irrigation strategy it is necessary to first know the soil's water holding capacity, the emitters' wetting area and the irrigation threshold value. According to experiments with avocado carried out by Ferreyra et al. (2007b) water may be depleted up to 30 to 40% of its availability in the soil (threshold irrigation) before watering again without affecting crop yields.

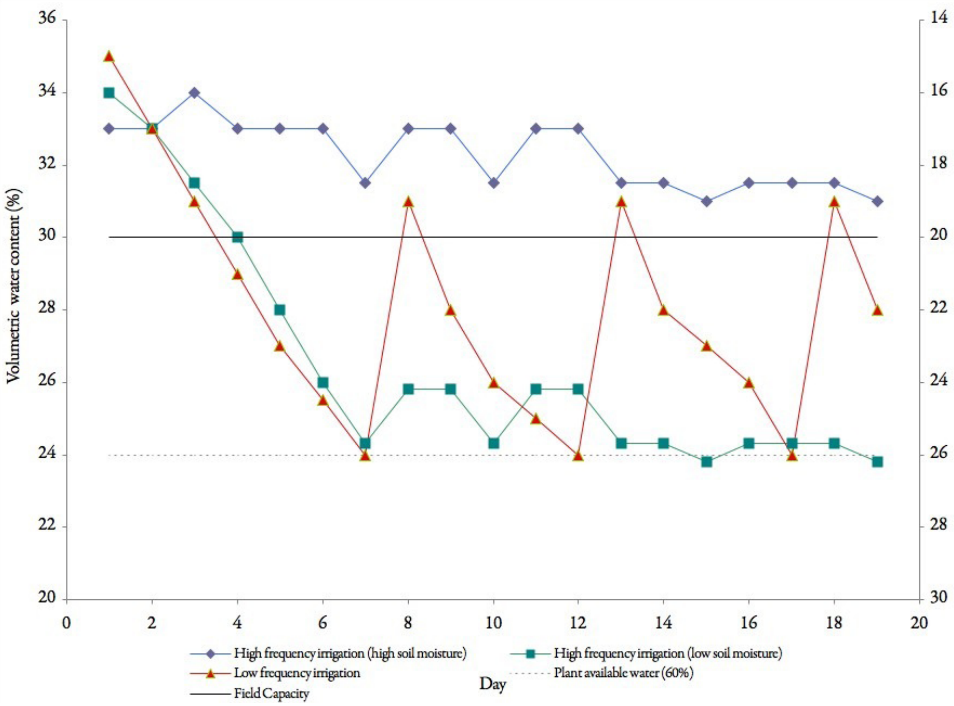

Figure 18. The influence of high and low irrigation frequencies on soil aeration. Total porosity = 50%; FC = Field capacity; AWD = Available water depletion.

In another study performed in a sandy loam soil (Ferreyra et al., 2007b; Table 3), avocado trees were watered with three different irrigation thresholds using a microsprinkler irrigation system. It was concluded that 60% reduction of the available moisture before watering, did not affect tree water status, tree performance or tree size. Plants watered with a threshold of 60% irrigation (watering in summer every 5 or 6 days) had an average stem water potential of -0.53 to -0.68 MPa at midday during summer (1 MPa = 1,000 centibars).

The same authors conducted a soil drying study to determine irrigation thresholds. Soil moisture, stem water potential, maximum daily stem contraction and stomatal conductance were measured. The experiment was conducted in February 2006 (summer in the southern hemisphere) with 6-year old 'Hass' avocado on seedling 'Mexicola' rootstock planted in a clay loam soil. In the trial 12 homogeneous trees were selected and irrigated daily with microsprinklers. Six plants were not watered for 13 days. Five days after water was withheld these trees showed physiological differences compared with the irrigated plants (control). The two treatments differed when approximately 30% of the available moisture in the soil was depleted. However, the parameters measured indicated that although differences were detected, the non-irrigated plants were not highly affected by water stress (Ferreyra et al., 2009). The irrigated trees continued taking water from the soil at the same rate, which is observed by looking at the decrease in the soil moisture curve's slope (Figure 19A), until 60% of available moisture was depleted. Throughout this period the non-irrigated and the irrigated plants maintained similar values for stomatal conductance (0.6 to 0.4 cm·s-1) (Figure 19D). The stem water potential (SWP) (Figure 19B) and the maximum daily trunk shrinkage (MDTS) (Figure 19C) are significantly different to the control after 5 days without irrigation, (40% of available water depletion).

Table 3. Effect of varying soil moisture depletion levels before irrigating on yield, size of fruit and water status of 'Hass' avocado on seedling 'Mexicola' rootstock in a sandy loam soil near Panquehue, Chile.

Treatment	Soil water depletion at time of irrigation	Yield (Kg/tree)		Size 50 – 32 (%)		SWP midday (Mpa)		Gs (cm s^{-1})		Water applied (m^3/ha)	
		2004/05	2005/06	2004/05	2005/06	2004/05	2005/06	2004/05	2005/06	2004/05	2005/06
T1	5%	40.6 a	45.7 a	33.0 a	47.0 a	-0.57 a	-0.61 a	0.28 a	0.30 a	6,771	10,220
T2	30%	38.7 a	53.0 a	28.0 a	52.7 a	-0.53 a	-0.58 a	0.31 a	0.28 a	6,996	10,241
T3	60%	41.1 a	47.8 a	28.0 a	79.5 b	-0.60 a	-0.68 a	0.35 a	0.25 a	7,116	10,572

T1 = irrigation when 5% of the available moisture (HA) depleted (irrigation pulse). T2 = irrigation when 30% of HA depleted. T3 = watering when 60% of HA depleted.
SWP midday = stem water potential measured at midday.
gs = stomatal conductance measured at noon.
Orchard spacing: 6 x 4 m (~20 x 13 ft.).
10,000 m3/ha ~ 3.3 acre-ft/acre _

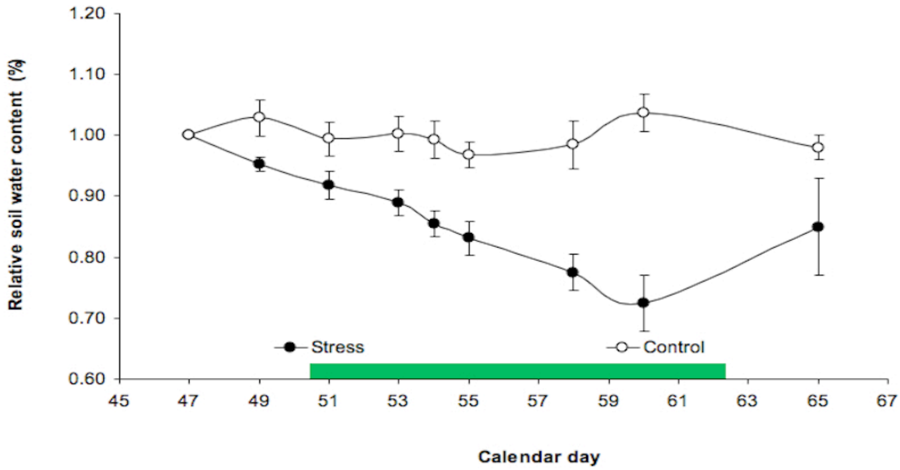

Figure 19 (A)

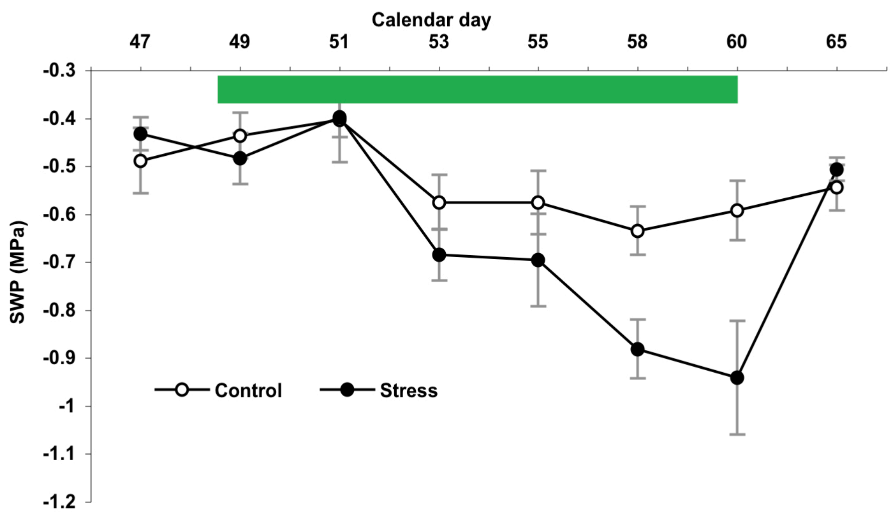

Figure 19 (B)

Figure 19. Effect of water stress on (A) the soil water content; (B) stem water potential (SWP); in 'Hass' avocado plants on seedling 'Mexicola' rootstock, February 2006, San Pedro, Quillota, Valparaíso Region, Chile. Each point represents the average of six measurements. Vertical bars represent standard deviation. The thick horizontal bar indicates the duration of the deficit.

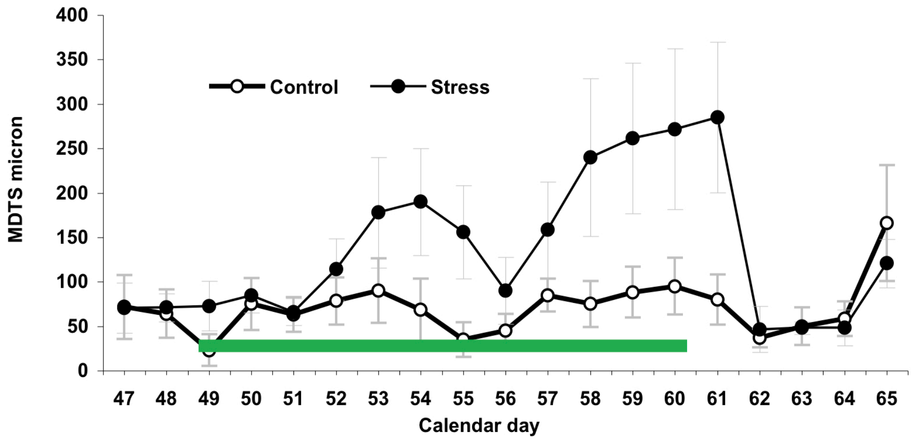

Figure 19 (C)

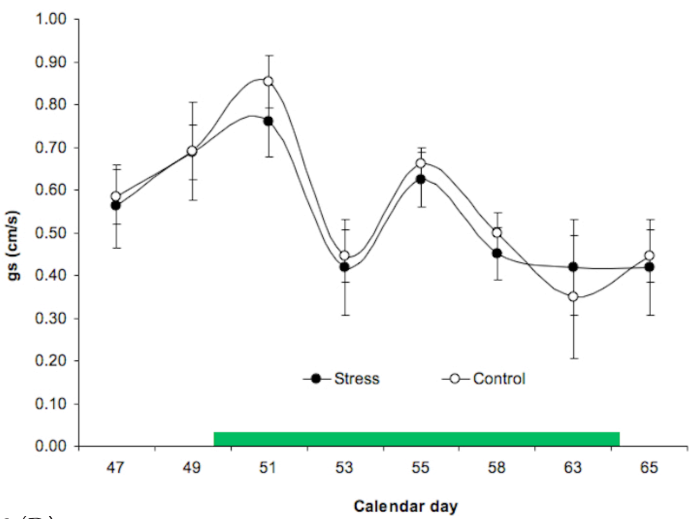

Figure 19 (D)

Figure 19. (Cont.)
Effect of water stress on (C) maximum daily trunk shrinkage (MDTS); and (D) stomatal conductance (gs) in 'Hass' avocado plants on seedling 'Mexicola' rootstock, February 2006, San Pedro, Quillota, Valparaíso Region, Chile. Each point represents the average of six measurements. Vertical bars represent standard deviation. The thick horizontal bar indicates the duration of the deficit.

In summary, according to field experience and scientific evidence, avocado trees grown in fine textured soils can be irrigated using a low frequency irrigation approach. This will optimize the water-to-air relationship necessary for good growth and productivity. However, it is necessary to determine irrigation frequency according to the soil moisture retention characteristics, using threshold irrigation between 30 to 40% depletion of available soil water content.

To implement low-frequency irrigation it is necessary to know the soil water holding capacity (which is a function of field capacity, wilting point and bulk density) as well as the effective root depth and the percentage of soil wetted (PSW) by the irrigation equipment. Table 4 shows how much water can be used (Available water depletion depth, AWDd) before watering with a 40% threshold for different soil textures. Also, at the bottom of Table 4, it is possible to see how AWDd is calculated. For example, in a clay loam soil, the available water in the above conditions is 20 mm (0.79 inch). If a 5 mm/day ETc (0.20 inch) is considered, it will be possible to water the soil every 4 days. As indicated above, the irrigation frequency depends on soil type, available water and the crop water demand that varies during the season.

Table 4: Soil physical properties and soil water depletion (mm) of different textured soils.

Texture	Da	Gravimetric moisture content (%)		UR	psw	H	Ha
	g cc^{-1}	FC	WP	(%/100)	(%/100)	(cm)	(mm)
Sand	1.65	9	5	0.4	0.5	70	9
Sandy Loam	1.50	14	8	0.4	0.5	70	13
Loam	1.40	22	12	0.4	0.5	70	20
Clay Loam	1.35	27	14	0.4	0.5	70	25
Sandy Clay	1.30	31	16	0.4	0.5	70	27
Clay	1.25	35	18	0.4	0.5	70	30

Da = Bulk density; FC = field capacity; WP = wilting point; UR = depletion fraction of available water; psw = percentage of wet soil; H = rooting depth; Ha = soil water depletion (soil water use) = ((FC - WP)/100 x Da H x UR x psw) x 10.
1 inch = 2.54 cm = 25.4 mm.

A good irrigation schedule, considers reference evapotranspiration (ETo), the crop coefficient (Kc) and soil moisture retention, data that gives a good approximation of the real crop irrigation requirements. The complementary use of probes to constantly measure the soil moisture (Frequency Domain Reflectometry, FDR) can improve estimating the crop water requirements and thereby reduce the volume of water lost through deep percolation, resulting in water cost savings and improving electrical energy use and cost as well as the water-to-air ratio in the soil.

Figure 20 provides an example of adjustments made to an irrigation program using continuous humidity sensors (FDR). When the irrigation was initiated while the soil water depletion was only 15 mm (0.6 inch), the available water in the soil measured with FDR sensors changed very slowly (the slope is almost

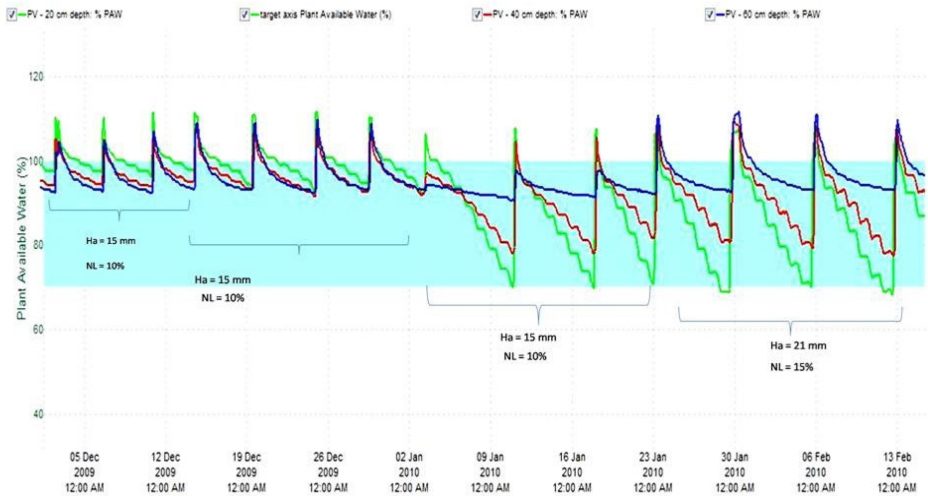

Figure 20. Setting example of an irrigation program through the use of continuous moisture sensors (FDR). Green Line is available water to the plant at 20 cm depth (~8 inches); red at 40 cm (~16 inches), and blue at 60 cm (~24 inches) depth. Between 100 and 60% is the usable water, which corresponds to 40% depletion of available water for plants. Ha = Soil water depletion and NL = Needed leaching (Leaching Fraction).

flat). This demonstrates that the plants had difficulties extracting water (the soil was too wet) indicating that the irrigation frequency was too high. When the soil water depletion before irrigation was increased to 21 mm (~0.8 inch), soil available water measured by the FDR shows sharper change (sharp slope), which means that the plant roots can easily extract water from the soil up to the next irrigation event. This could be because when oxygen levels are low (<17% for avocado), plants inhibit transpiration that will affect their growth (Tables 1 and 2).

In some orchards, farmers who try to avoid root asphyxia, over restrict water application. This could result in water stress affecting fruit size and vegetative growth. Be aware of the soil characteristics, having an irrigation program and keeping track of soil moisture will certainly avoid excesses or deficits in soil moisture that could affect production.

In some cases, particularly in orchards planted on hilly terrain, there are more trees with root asphyxia symptoms at the bottom of the orchard, (Figure 21). These problems are normally associated with drainage areas, so it is necessary to improve field surface drainage to drain excess water that accumulates in these areas. An error in the strategy to address root asphyxia problems can affect significantly the yield and consequently an increase in water and energy costs per kilogram of fruit produced.

SUMMARY

One of the causes for low yields in avocado orchards in Chile is that a large number of orchards are planted in soils with low air capacity (fine-textured soil such as clays, clay loams and loams) which is unfavorable for root health due to periods of low oxygen, regardless of duration. Improper irrigation practices will make this problem worse.

Many experiments show that the avocado grows well in soils with a 30% air capacity. Avocado trees begin to show root asphyxia symptoms when the soil oxygen content falls below approximately 17%. For proper avocado root and canopy development it is necessary to maintain an appropriate water-to-air balance in the soil. This simple idea is difficult to implement, especially in fine textured soils, because with each irrigation the water content increases and soil aeration decreases significantly. There is a slow drainage in the larger diameter pores until the soil reaches field capacity. Therefore, an irrigation program for avocado needs

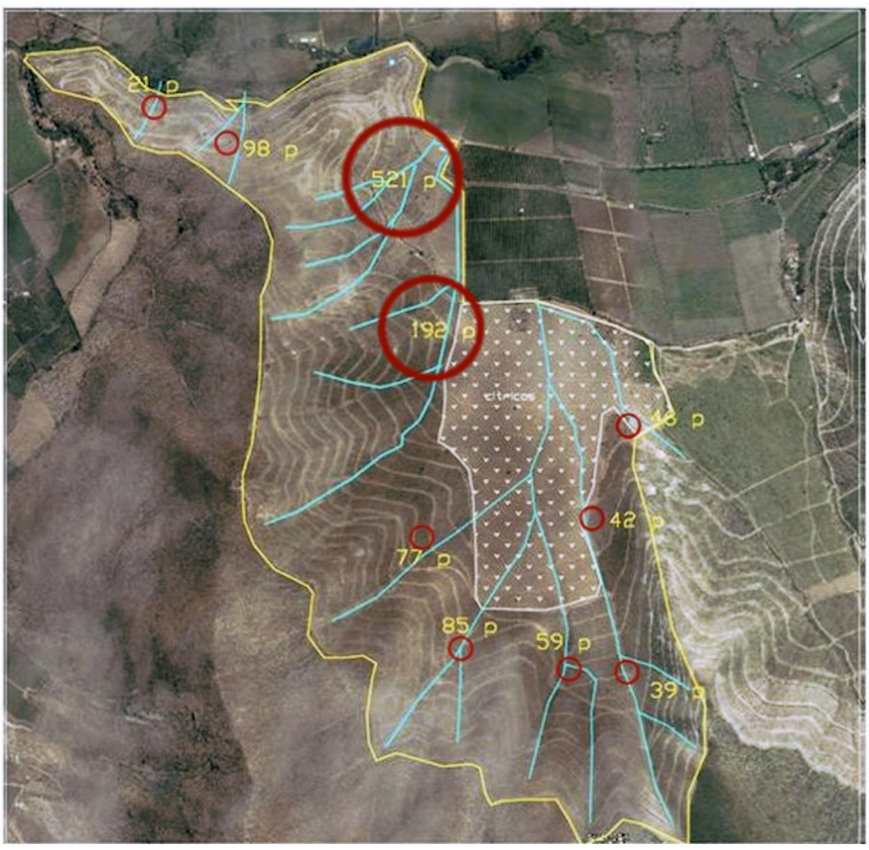

Figure 21. Concentrated zones of plants with root asphyxia (Red circles).

to consider not only the water requirements but also an analysis of the soil physical conditions in a holistic manner, considering the interaction between aeration, moisture retention and soil mechanical resistance, topics that were discussed in this paper.

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**The Institute of Agricultural Research's (INIA) mission is the creation, adaptation and transfer of technologies to ensure that the agricultural sector will contribute to the safety and quality of food produced in Chile, in addition to provide a competitive and sustainable response to the challenges of rural development.*

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