EFFECT OF IRRIGATION AND SOIL TYPE ON ROOT GROWTH AND DISTRIBUTION OF *VITIS VINIFERA* L. CV. NERO D'AVOLA GROWN IN SICILY

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Key words: soil types, irrigation, predawn water potential, root, Nero d'Avola cv.

Abstract
The trial was carried out in a Nero d'Avola vineyard, grafted onto 1103Paulsen, and located in Alcamo D.O.C. area (Sicily). Vines were trained to a vertical trellis system, spur pruned and drip irrigated. Three treatments were applied: A) vines grown without irrigation water; B) vines irrigated when the pre-dawn leaf water potential was above -0.7 MPa and to maintain pre-dawn leaf water potential at value below -0.4 MPa until harvest; C) vines irrigated in order to maintain pre-dawn leaf water potential at value below -0.4 MPa, from budbreak to harvest. Three clay soil types were present in the vineyard: Entisol, on the top of the hill, Inceptisol, halfway down the hill and Vertisol, at the bottom of the hill. The distribution of the root system in the different soil types and in relation to the different irrigation treatments was determined by using the contact method. Irrigation was the most important factor in determining the quantity and distribution of roots, even if it was also noted that the irrigation strategy must be calculated in relation to the type of soil or vice-versa, so that the type of soil determines the most suitable irrigation strategy. For the study of the relationships between root systems and area, it is necessary to take the efficiency of the root systems into account, especially in conditions in which the various limiting effects are reduced, as happens in the dry environments where irrigation is used.

Résumé
L'essai a été effectué dans un vignoble du cépage Nero d'Avola greffé sur 1103 Paulsen dans un terroir de la D.O.C Alcamo en Sicile. Le système de conduite des vignes était à espalier, la taille à cordon coursonné et l'irrigation à goutte a goutte. On a été confrontés trois types de traitements: A) vignes non irriguées; B) vignes irriguées quand le potentiel hydrique foliaire (potentiel de base) était au dessous de –0.7 MPa, pour maintenir le potentiel hydrique foliaire de base au dessous de –0.4 MPa jusqu'à la récolte; C) vignes irriguées en maintenant le potentiel hydrique foliaire de base au dessous de –0.4 MPa du débourrement à la récolte. Dans le parcelle de l'essai étaient présents trois types de sol argileux: Entisol dans le partie haute de la colline, Inceptsol à moitié de la colline et Vertisol à la vallée de la colline. On a déterminé la distribution du système racinaire de la vigne dans les différentes types de sol par rapport aux différents traitements hydriques en emploient la méthode du contact. L'irrigation a été le facteur le plus important pour la croissance et la distribution du système racinaire; on a aussi noté que la stratégie de l'apport hydrique doit être calculée par rapport au type du sol ou vice-versa; par conséquence c'est le type de sol que détermine la stratégie d'irrigation la plus appropriée. Pour étudier les rapports entre le système racinaire et le feuillage et toute la biomasse il faut tenir en compte l'efficience du système racinaire, particulièrement dans les conditions dans lesquelles les divers effets limitants sont réduits, comme se vérifie dans les endroits secs où on emploie l'irrigation.

Introduction
The growth of root (length and mass densities), their thickness, its distribution in depth depends on different factors, genetic component (scion-rootstock combination) (Southey et al., 1988; Smart et al., 2001; Stevens et al., 1994), soil environment (physical and chemical characteristics) (Conradie, 1988; Morlat et al. (1993); Rowe, 2003) cultural techniques (water regime and irrigation system, plant spacing, trellis system, soil management, fertilization) (Archer et al. 1988; Dry et al., 2000; Barbagallo et al., 2004; Mapfumo et al., 1994; Morlat et al., 2003; Southey, 1988; Stevens et al., 1995; Van Huyssteen, 1988; Van Zyl, 1988; Wheaton, 2002).

The numerous current available methods of analysis of root systems, suitable for field studies, have low accuracy and different targets. Moreover, the results of these studies are not easily comparable.
The root development is also due to supply of carbohydrates from leaf photosynthesis during the season and a positive correlation between below- and above-ground growth was found by different authors (Rowe, 2003; Archer et al., 1988; Hunter et al., 1995; Hunter et al., 2001). Even if, this relationship could be compromised by the low efficiency both of roots and of canopy (Hunter et al., 1992; Morinaga et al., 2003) which could be caused by technical management of vineyard or environmental stress.
The aim of this paper is to study the effect of soil type and irrigation regime on root development and its influence on above-ground growth in Nero d'Avola grapevine, the one of most important cultivars diffused in Sicily.

Material and Method

The study was carried out in a vineyard situated within the Alcamo D.O.C. zone, which is itself located in the hinterland of western Sicily (fig. 1). The experimental vineyard is given over to a Nero d'Avola cultivar grafted onto 1103 P rootstock, in its fourth year of production. The distance between the plants is 240cm inter-row and 95 cm in-row for an overall density of 4386 plants per hectare. The vines were upwards-trained on vertical trellis with spur pruning system. Two buds-spur were used and spaced approximately 20 cm apart on the single cordon. Suckering were applied before flowering.
The ground is dug mechanically so as to avoid the growth of weeds. The vineyard is irrigated using a drip system (4 litres per hour). The experimental zone, which covers an area of about 1 hectare, is on a south-facing hillside ranging in height from 300 to 320 metres above sea level with a maximum incline of about 13%. The vineyard is part of a thermometric regime of continental thermal soils (Thornthwaite e Mather, 1957), characterised, during the four years of the experiment, in the period from March to October, by average maximum temperatures ranging from 13.5°C to 32°C (in March and August respectively) and average minimum temperatures ranging from 6°C to 22.4°C (again in March and August respectively). The lowest temperatures of the four-year during the period from May to August have constantly been higher than the average of the last thirty years, while the highest temperatures of the four-year period have been lower than those of the last thirty years, except during the months of June and July. There has, however, been greater rainfall in the four-year period than the average recorded for the last thirty years, especially in June, August, September and October (fig. 2).
The pedologic study made through opening and observation of 20 soils profiles and several drilled, has allowed to characterize three kind of soils, described in the following part, which are situated in the top, in the middle and in the lower part of the slope. These three soils have been classified according to Soil Taxonomy (Soil Survey Staff, 1999) and WRB (IUSS, 1999).
Soil of the upper part: *Entisol* (E). According to Soil Taxonomy these soils are Typic Xerorthents, fine, mixed, termic continental on Tortorian clays, Alfio series. According to WRB they are Hipereutric Regosols. The soil profile is Ap-C, the wet soil colour is olive brown, (2.5Y 4/4). The structure is angular polyhedric. The C layer is massive. When the soil is not cultivated appears cracked. The porosity is high up to 50-60 cm of depth. The texture is clayey with a 45 % of clay. The amount of skeleton is generally low. They have a normal amount of total limestone, with a low active part. The pH is 8.1. The base saturation is high. The organic matter is scarce. Total salinity is absent. Soils in slight slope: *Inceptisol* (I). According to Soil Taxonomy, they are Vertic Haploxerepts, Rapitalà series: fine, mixed, termic continental on Tortorian clays, Alfio series. According to WRB they are Vertic Cambisol. They are located in an area with an average slope of 12-13 %. The soil profile is Ap-Bw-C, very deep (> 100 cm). The wet soil colour is from olive brown, (2.5Y 4/4) to olive (5Y 4/3). The structure is angular polyhedric in the Ap layer and it becomes angular polyhedric coarser, strong in Ap2 and in Bw. When the soil is not cultivated, the cracks affect the soil for more than 40 cm. The porosity is high in the top soil and it decreases with depth. In Bw layer there are slikensides. The texture is clayey with a 45 % of clay. The amount of skeleton is generally low or absent. They have a normal amount of total limestone, with a low active part. The pH is 8.1. The base saturation is high. The organic matter is insufficient in all the soil profile. Total salinity is very low. There are vineyard roots in about 80 cm of depth.
Soils of the lower part of slope: *Vertisol* (V). according to Soil Taxonomy they are Chromic Haploxererts, Giardinello series, fine, mixed, termic continental on Tortorian clays. According to WRB they are Chromic Cambisol. They are located in an area with an average slope of 4-5 %. The soil profiles is Ap-Bss-C very deep (> 100 cm). The wet soil colour is olive (5Y 5/3). The structure is granular and angular polyhedric, coarse, strong in Ap2 layer, while it has a wedge shape in the lower layer (Bss). When they are not cultivated there are cracks up to 80-100 cm of depth. The porosity is high in the top soil and it decreases with depth. In

the Bw layer there are slikensides. The texture is clayey with a 50 % of clay. The amount of skeleton is generally low. The amount of total limestone is from normal to low with a low active part. The pH is from 8.1 to 7.9. The base saturation is high. The organic matter is low or insufficient. Total salinity is low. Vineyard roots affect the soil for about 100 cm of depth.
The three different soil-type areas, each planted with about 1,000 plants, have been given three different treatments since the first year of production: Treatment A: vines grown without irrigation water; Treatment B: an irrigated cultivation regime, with irrigation starting when the "predawn" water potential reached values lower than –0.7 MPa, maintaining the predawn potential at levels not lower than –0.4 MPa until harvest.
Treatment C: an irrigated cultivation regime, maintaining "predawn" water potential at values no lower than –0.4 MPa from budbreak to pre-harvest period. "Predawn" water potential was determined using a Scholander chamber every 4 days on 15 leaves per treatment, opposite the first grape-bunch. In January 2004 a trench was dug for irrigation treatment in each soil-type area. The trenches were 2 metres long inter- and in-row and 1 metre deep.
Using the contact method (Smith et al. 2000) the number of roots intercepted were counted and divided into three groups depending on their diameter: small, from 0.15 to 2.5 mm; medium, from 2.5 to 3.5 mm; large, > 3.5 mm.
For 15 plants, yield at the harvest and the amount of pruning mass taken away during winter was measured.
The results were subjected to analysis of variance, using a factorial design with type of soil and type of irrigation as main factors. For the percentage of root system distribution, a transformation of the data was carried out before variance analysis. A linear regression between the quantity of roots and the quantity of grapes plus pruning mass and between the "predawn" water potential and the quantity of grapes plus pruning mass produced was also carried out. This data refers to R^2 and its relative significant.
The statistical analysis was carried out using the statistics programme SYSTAT 9.0 (copyright 1990, SYSTAT, Inc).

Results and Discussion

In the four-year period of the research, the first irrigation was applied after fruit set for treatment C and after pre-veraison for treatment B. Irrigation was performed when the average values of the predawn potential were -0.3 MPa and –0.7MPa respectively. For treatment C, seven irrigation interventions were made, while for treatment B four were carried out, making a total of 980 m^3/ha and 560 m^3/ha respectively. The plants under dry condition reached "predawn" water potential levels between –0.4 MPa and –0.7 MPa from fruit set to veraison and between –0.7 MPa and -1.3 MPa from veraison to harvest (fig. 3).
Variance analysis highlighted a significant effect of both the main factors (soil and cultivation techniques) on the total number of root contacts as well as their interaction, which provided the most important results (tab. 1). Irrigation was certainly the most evident of the principal factors: the average number of root contacts increased in all three types of soil as the amount of water administered increased, passing from 97 in dry conditions to 128 in treatment B and to 141 in treatment C (fig. 4).
The number of root contacts was similar in the *entisol* and the *vertisol* (132 and 129 respectively) and lower in the *inceptisol* (105) (fig. 5). The different reaction of the different types of soil was due to irrigation. Under dry cultivation, indeed, there were no significant differences between the different types of soil (fig. 6a). What is more, in the *entisol*, the difference in the total number of contacts was due to the values found in treatment C (fig. 6b), while in the *vertisol* a significant increase in contacts was found in treatment B (fig. 6c). In the *vertisol*, the irrigation strategy adopted for treatment C brought about rapid over-saturation and an excessive compacting of the soil mass with conditions that were barely "habitable" for the roots. The most suitable soil conditions for the development of root systems was found in the *entisol* in the layer nearest the surface. This was caused by an important increase in porosity and water infiltration. Therefore, in this soil, the strategy of irrigation linked to treatment C was the most effective for the development of root systems. Finally, behaviour in the *inceptisol* was mainly conditioned by the characteristic sloping conditions of this type of soil.
The effects described and the different behaviour of treatments B and C and in the three different types of soil were due to the number of roots whose diameter was less than 2.5 mm, in that, in the variance analysis, no importance was found regarding the number of contacts between medium and large roots (tab. 2). The percentage of roots with a diameter less than 2.5 mm varied from 63% in the treatment A to 69% and 70% respectively in the treatment B and C (data not shown).
As far as the distribution of root systems is concerned, the results obtained show that the "type of soil" particularly influenced the number of in-row contacts, while the "cultivation techniques" had an influence

both in-row and inter-row (tabs. 3 e 4), with increases in both cases when the quantity of water provided increased (figs. 7 a e b).
Besides, statistical analysis of these parameters demonstrated the great importance of interaction between "soil x cultivation techniques" (tabs. 3 e 4), according to the different behaviour noticed in the *entisol* and the *vertisol*. The considerations developed in the comment on the "total number of root contacts" variable also stand. What is more, while in the *entisol* the largest presence of root contacts was found inter-row and in-row space (figs. 8 a e b), in the *vertisol* the differences with other types of soil were only recorded in-row space (fig. 8 a).
The depth distribution of roots expressed as a percentage of the total number of contacts, shows that, on average, 64.7 % of root contacts were found in the layer of soil at a depth between 41 and 80 cm, 24.3% in the layer of soil at a depth between 0 and 40 cm and only 10.99% in the layer of soil deeper than 80 cm (fig. 9). The soil type influenced the distribution of root systems, especially in the *entisol* where a greater number of root contacts was found in the superficial layers, while in the *vertisol*, root contacts were deeper in general. Indeed, in this last soil type, the total number of root contacts was about 25 in the layer of soil at a depth between 0-40cm, more than 80 up to a depth of 80 cm and more than 20 at a depth of more than 80 cm. The respective values of the *entisol* and the *inceptisol*, on the other hand, were 50, 70 and 3 and 12, 70 and 18 (fig. 10). The irrigation regime, which, as we have seen in figure 3, significantly influenced the total number of root contacts, even at a great depth thus modifying the distribution in the different layers (fig.11). The percentage distribution of roots at different depths, however, has not significantly been influenced by treatments. Indeed, the analysis of variance only showed a significant effect for the "type of soil" factor regarding the distribution percentage of root contacts at the three different depths (tab. 5). In particular, it is the *entisol* which differs more significantly. In the variance analysis, indeed, the root systems are shown to have a more superficial development, with over 36% of contacts observed in the layer of soil at a depth between 0 and 40 cm in comparison with a value of about 5% in the layer of soil deeper than 80 cm. This is in contrast with the percentage results for the *vertisol* (21%, 15% for the 0-40 cm layer and for the layer of soil deeper than 80 cm respectively) and the *inceptisol* (13%, 20% respectively) (data not shown). This behaviour confirms the greater level of porosity in the superficial layers of the *entisol.*
Besides, at a greater depth, an important effect in the interaction between the "type of soil and the water regime" was noticed (tab. 5) with an increase of root contacts in the *entisol* for the treatment in which the greatest quantity of water was provided (treatment C) (data not shown). The relationship between the root systems and the above ground, showed a very low, and not significant, R^2 value (0.13). Only in the dry treatment did the increase in the number of root contacts correspond to a proportional increase in the biomass produced in terms of yield and pruning mass (tab.6) In agreement with several researchers (Rowe, 2003; Archer et al., 1988; Hunter et al., 1995; Hunter et al., 2001) a correct study of this relationship requires an precise assessment of the efficiency of absorption of root systems and not only a consideration of the quantity of root number. Indeed, the yield and pruning mass are inversely correlated, in a highly significant way (R^2=0.88), to the average values of the "predawn" water potential during the vegetative season (tab. 6).

Conclusions

The results obtained show, in the conditions under study, that irrigation was the best way of maximising the potential of a "terroir", and from this we were able to distinguish between different potentials.
Indeed, irrigation was the most important factor in determining the quantity and distribution of roots, even if it was also noted that the irrigation strategy must be calculated in relation to the type of soil or vice-versa, so that the type of soil determines the most suitable irrigation strategy. For the study of the relationships between root systems and above-ground, it is necessary to take the efficiency of the root systems into account, especially in conditions in which the various limiting effects are reduced, as happens in dry environments where irrigation is used.

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Fig. 1. Experimental farm: Tenuta Rapitalà
4198000 N-330000 E (UTM D50)
Altitude: 330 m s.l.m.

Fig. 2. Climatic characterization of D.O.C. Alcamo area: climatic factors (thirty-year) and climatic data (four-year)

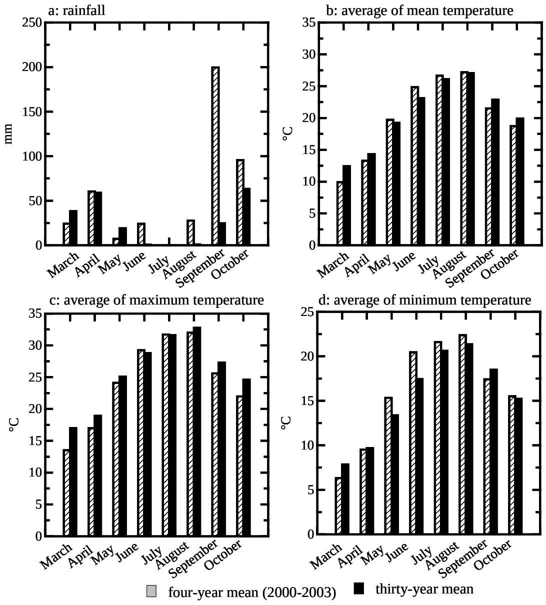


Fig. 3. Predawn water potential and timing of irrigation (average of 2000-2003 years) during growth season

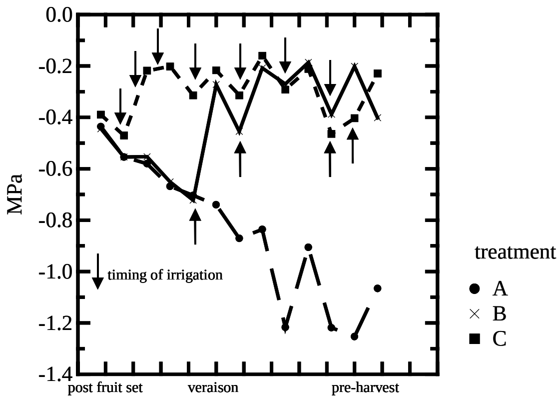


Fig. 4 – Effect of irrigation treatments on number of root contacts

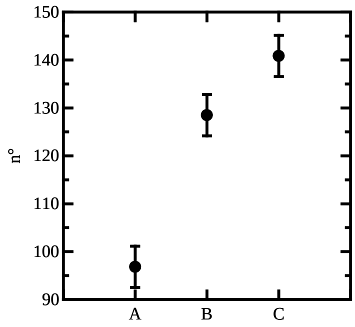


Fig. 5 – Effect of soil types on number of root contacts

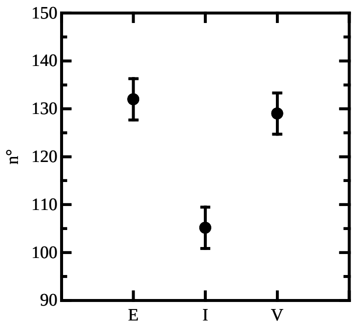


Fig. 6 – Effect of soil types on number of root contacts for different irrigation treatments

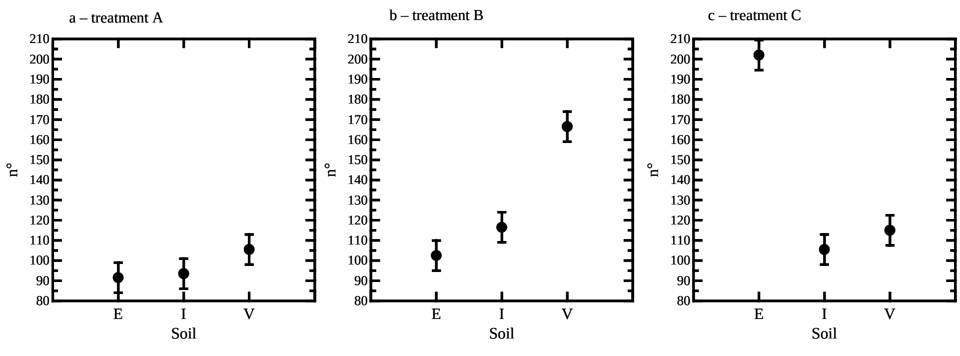


Fig. 7 – Effect of irrigation treatments on number of root contacts

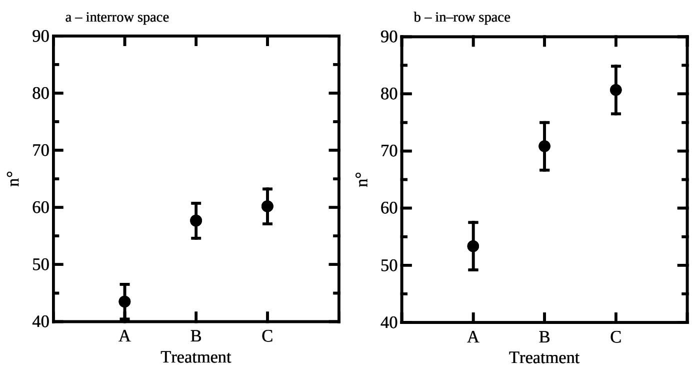
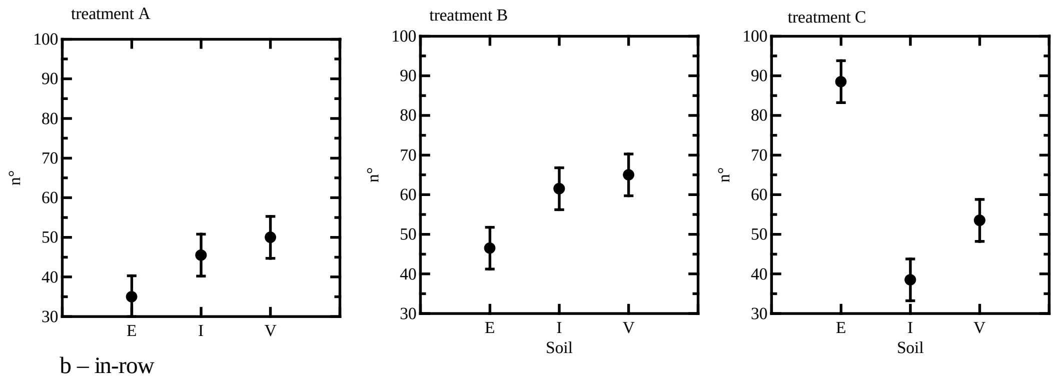


Fig. 8 – Effect of irrigation treatments on number of root contacts for different soil types

a – interrow



b – in-row

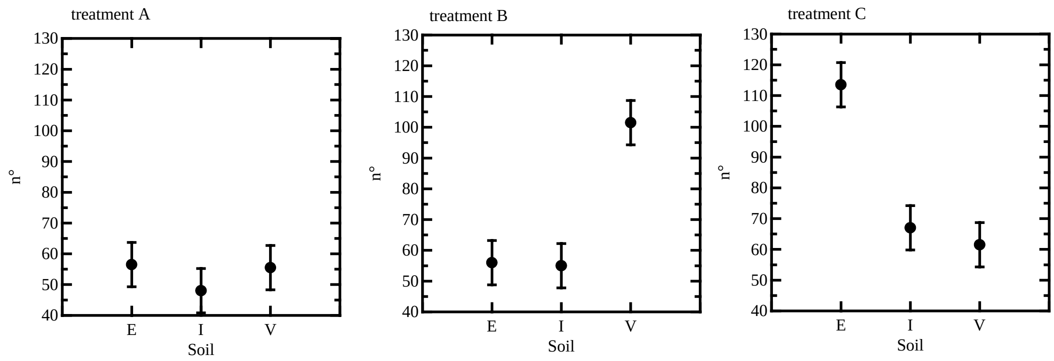


Fig. 9 – Influence of soil-depth on root-system distribution (%)

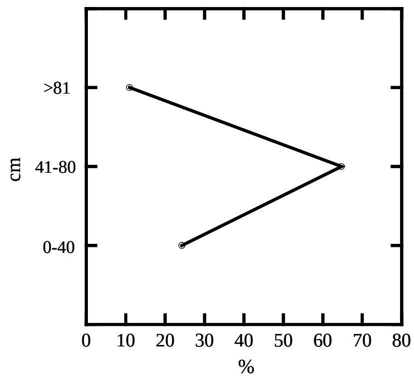


Fig. 10 – Influence of soil-depth on number of root contacts in different soil types

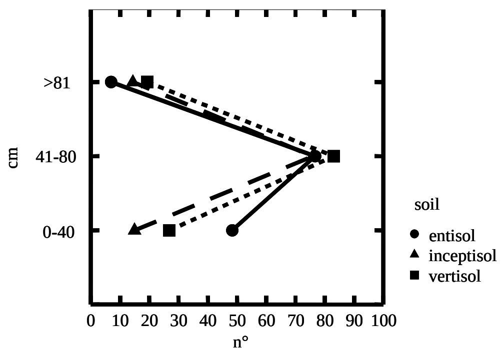
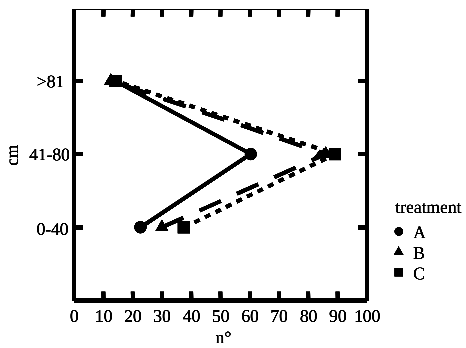


Fig. 11 – Influence of soil-depth on number of root contacts in different irrigation treatments



Tab. 1 – Results of analysis of variance: Number of root contacts

R^2=0.96**

Sources	F-ratio	p
Soil	11.7	0.00
Treatment	27.8	0.00
Soil x Treatment	30.3	0.00

*=sign. for p<0.05; **=sign. for p<0.01

Tab. 2 – Results of analysis of variance: Number of root contacts for different root diameters

Root diameter	∅ < 2.5 mm		∅ 2.5 mm ≤ ≥ 3.5mm		> 3.5mm	
Sources	F-ratio	p	F-ratio	p	F-ratio	p
Soil	17.7	0.00	1.9	0.20	1.3	0.32
Treatment	29.3	0.00	1.2	0.35	0.2	0.78
Soil x Treatment	22.9	0.00	3.6	0.06	3.3	0.06
R^2	0.95**		0.70**		0.64**	

*=sign. for p<0.05; **=sign. for p<0.01

Tab. 3 – Results of analysis of variance: Number of root contacts on interrow space

R^2=0.89**

Sources	F-ratio	p
Soil	2.3	0.16
Treatment	8.7	0.01
Soil x Treatment	13.5	0.00

*=sign. for p<0.05; **= sign. for p<0.01

Tab. 4 – Results of analysis of variance: Number of root contacts on in-row space

R^2=0.90**

Sources	F-ratio	p
Soil	5.9	0.02
Treatment	11.1	0.00
Soil x Treatment	11.9	0.00

*=sign. for p<0.05; **= sign. for p<0.01

Tab. 5 – Results of analysis of variance: Percentage of root contacts for different soil-depths

Soil-depths	0-40 cm		41-80 cm		> 80 cm	
Sources	F-ratio	p	F-ratio	p	F-ratio	p
Soil	26.3	0.00	14.6	0.00	19.5	0.00
Treatment	0.03	0.97	1.9	0.21	2.8	0.11
Soil x Treatment	1.5	0.27	0.5	0.71	7.6	0.01
R^2 and sign p	0.87**		0.80**		0.89**	

*=sign. for p<0.05; **= sign. for p<0.01

Tab. 6 – Values of predawn Ψ, yield and pruning mass, number of root contacts for soil types and irrigation treatment. Determination coefficient obtained by linear regression: 1) "predawn" water Ψ-yield + pruning mass; 2) number of root contacts- yield + pruning mass

soil type	irrigation treatment	predawn Ψ MPa	yield + pruning mass g	root contact n°	yield g	pruning mass g
E	A	-0.91	1574	92	1262	312
E	B	-0.40	4834	103	4090	744
E	C	-0.31	4446	202	3730	716
I	A	-0.84	2582	94	2070	512
I	B	-0.42	4840	117	4260	580
I	C	-0.30	5129	106	4444	685
V	A	-0.79	3548	106	2840	708
V	B	-0.39	4655	167	4130	525
V	C	-0.28	5305	115	4525	780
		R^2=0.88 **		R^2=0.13 n.s.		

n.s.= not significant; **= sign. for p<0.01