Root system and water extraction variability for sunflower hybrids

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ABSTRACT

Root traits and soil water extraction of fifteen genotypes were characterized in five greenhouse experiments. The objective was to evaluate the genotypic variability and to identify possible new strategies in plant breeding for drought-stressed conditions. The root traits were characterized at the flowering stage by the root length density (RLD) and the effective rooting depth (Z). The performance in soil water extraction was characterized by the fraction of extracted soil water (EW). It was estimated from soil drying experiments conducted on plants at different stages. Z and EW were used to calculate an indicator of the amount of extractable soil water (EW_{gen}). Wide variability of those traits was observed among the genotypes. Four classes of genotypes were found with a maximal difference of 10% between the extreme values of fraction of extracted soil water. Water depletion kinetics was different between the experiments but the fraction of extracted soil water was stable for each genotype. A large genotypic variability for the indicator of the extractable soil water was also observed. This variability resulted from different combinations of effective rooting depths and fractions of extracted soil water. These traits might be of interest for breeding cultivars well adapted to water stress conditions.

Key words: drought stress – extracted soil water – genotype – rooting depth – root length density – sunflower.

INTRODUCTION

Water deficit is the most predominant abiotic stress experienced by sunflower (*Helianthus annuus* L.) especially because most sunflower crops are cultivated under rainfed conditions (Goyne et al., 1978; Yegappan et al., 1982; Connor et al., 1985). To sustain production in such limiting environmental conditions, sunflower drought tolerance should be increased. It could be done through the selection of plants able to limit the water deficit they undergo under limited soil moisture conditions. One way could be to improve the plant performance in soil water extraction, either by increasing the soil depth explored by roots (Connor and Hall, 1997) or by increasing the fraction of soil water extracted by the plant.

The objective of this study was to evaluate the genotypic variability in the root system architecture and in the soil water extraction for a panel of commercial genotypes. Five greenhouse experiments were conducted between 2005 and 2007 on 15 genotypes. They represented 40 years of currently used cultivars; 10 are old and modern hybrids currently cultivated in France and 5 are experimental hybrids, which could be the next cultivars in France (F. Vear, pers. comm.). The root traits were characterized by the root length density and the effective rooting depth. The performance in soil water extraction was characterized by the fraction of extracted soil water. It was estimated at the end of a drying cycle.

MATERIALS AND METHODS

Plant materials and growth conditions

Five experiments were conducted in a greenhouse in Montpellier (France, 43°35'N and 3°58'E) from 2005 to 2007 (Table 1). 15 genotypes with contrasted phenology, architecture, photosynthesis and productivity were studied (Table 2). Plants were grown in plastic pots in Exp. 1 to 4 and in PVC columns in Exp. 5 filled with a mixture of loamy soil, sand and compost at the same volume. Each genotype was characterized by 6 plants in Exp. 3, 4, 5 and five plants in Exp. 1 and 2. Pots were installed in order to obtain a culture density of six plants per square meter. In order to avoid water deficit, plants were irrigated four times per day with a one-tenth Hoagland solution corrected with minor nutrients. Irrigation was stopped when the plant had 6, 12 or 14 full-expanded leaves respectively in Exp. 1, 3 and 4. In Exp. 2 irrigation was stopped when the plant reached the floral bud stage E1 (CETIOM, 2004). The natural light in the greenhouse was supplemented with sodium lamp (250 µmol m^{-2} s^{-1}) giving a photoperiod of 12h. Temperature in the greenhouse was maintained between 16°C and 30°C. Environmental conditions for the experiments are summarized in Table 1.

Table 1. Mean characteristics of the five experiments

Exp N°	Sowing date	Mean value of Temperature (°C)	Mean value of Vapour Pressure deficit (kPa)	Mean of daily cumulative PPFD (mol $m^{-2} d^{-1}$)	Number of genotypes
1	21 November 2005	18.4	2.12	25.13	15
2	19 November 2006	23.1	2.84	26.19	10
3,5	15 February 2007	23.5	2.91	23.58	10
4	3 April 2007	23.3	2.87	32.69	10

Table 2. Studied genotypes in the different experiments and their registration years

Genotype	Exp N°	Registration year
Peredovik	2, 3, 4	1960
Primasol	1, 2, 3, 4	1978
Albena	1, 2, 3, 4	1988
Vidoc	1, 2, 3, 4	1989
Santiago	2, 3, 4	1993
Melody	1, 2, 3, 4	1996
Sanbro	2, 3, 4	1997
Prodisol	1, 2, 3, 4	1998
LG5660	1	1998
Pegasol	1	2001
VAQxPAR6	2, 3, 4	2003[1]
VDQxOPB4	1	2003[1]
VDQxPPR9	1	2003[1]
XRQxPPR9	1	2003[1]
XRQxPST5	2, 3, 4	2003[1]

[1]Experimental breeding year

Measurements

Environmental conditions were measured continuously for all experiments. Air temperature and relative humidity were measured with a capacitive hygrometer (HMP35A Vaisala, Oy, Helsinki, Finland). Incident photosynthetic photon flux density (PPFD) was measured with a quantum sensor (Campbell PKS 215, Campbell Scientific Ltd, Shepshed, Leicestershire, England). Data were collected every ten seconds and means were stored every 1800s in a datalogger (CR10, Campbell Scientific Ltd).

Plant leaf area was estimated just before stopping irrigation in Exp 1 to 4 and at flowering stage in Exp. 5, by measuring the length and width of leaves. In Exp. 5, soil column was stratified per 10 cm for the first 20 cm layer and per 20 cm for the next. In each layer, roots were harvested and separated in thin or "structural" roots. Roots with a diameter of less than 2 mm were considered as thin. A 2-meter thin roots sample was picked from the first 10 cm soil layer. The root dry weight of this sample (DW_{2m}) and the DW (g) of the two classes of roots were estimated after drying at 60°C for 48h. The root mass length (Lm, cm g^{-1}) was calculated as the thin root length per unit of thin root mass:

$$Lm = 200 / DW_{2m} \qquad \text{(Eq. 1)}$$

The root length density (RLD, cm cm^{-3}) is the length of thin roots per unit of soil volume explored by the root system. It was calculated for each soil layer as follows:

$$RLD = \frac{Lm \; DW_{thin}}{V} \qquad \text{(Eq. 2),}$$

RLD, root length density (cm cm^{-3}); DW_{thin}, dry weight of thin root in the considered soil layer; V, volume of the considered soil layer.

The effective rooting depth for water extraction (Z, cm) was estimated as the root depth for which the root length density was more than 1cm cm^{-3}. As proposed by Gregory (1994), Z was determined from linear regression between the depth of a layer (Y, cm) and the logarithmic value of the root length density.

$$Y = a \ln RLD + Z \qquad \text{(Eq. 3)},$$

Y, soil depth; a, coefficient of root length density distribution; RLD, root length density; Z, effective rooting depth.

In Exp. 1 to 4, a drought stressed treatment was applied stopping the irrigation at a determined phenological stage. The evening prior to the beginning of the treatment, all pots were fully watered and allowed to drain overnight. The following morning, pots were weighed to determine the initial soil water content (SWC_i). To prevent soil evaporation, the pots were enclosed in plastic bags. The plant transpiration rates were estimated by weighing each pot every day. The lower limit of soil water content (SWC_{min}) was assumed to have occurred when the plant transpiration remained constant during several successive days and reached 10% or less than that of well watered plants.

The soil water content (SWC, g g^{-1}) was estimated by weighing soil samples after drying at 105°C during 72 hours.

$$SWC = \frac{FW_{soil} - DW_{soil}}{DW_{soil}} 100 \qquad \text{(Eq. 4)}$$

SWC, soil water content; FW_{soil}, soil fresh weight; DW_{soil},soil dry weight

The fraction of soil water extracted by the plant (EW) was estimated as follows:

$$EW = \frac{SWC_i - SCW_{\min}}{SWC_i} 100 \qquad \text{(Eq. 5)}$$

Estimation of the amount of extractable soil water

The effective rooting depth (Z) and the fraction of soil water extracted by the plant (EW) were used to calculate an indicator of the amount of extractable soil water for each genotype (EW_{gen}, mm) relative to a standard condition. The chosen reference was a sunflower with an effective rooting depth of 1800 mm (Angadi and Entz, 2002) growing in a soil with 0.13 mm mm^{-1} of available soil water (Ratliff et al., 1983). EW_{gen} was calculated as follows:

$$EW_{gen} = \left[\frac{EW_i}{\frac{1}{n}\sum_{i=1}^{n} EW_i} 0.13 \right] \left[\frac{Z}{\frac{1}{n}\sum_{i=1}^{n} Z_i} 1800 \right]$$

(Eq. 6)

EW_{gen}, amount of extractable water for the genotype i; n, number of studied genotypes (10)

RESULTS AND DISCUSSION

Root traits: root length density and effective rooting depth

As illustrated in Fig. 1, the pattern of the evolution of the vertical distribution of root length density was similar for all the genotypes. The root length density decreased exponentially with soil depth. 85% of root length density was observed in the first 40 cm of soil depth (Fig. 1). These results obtained in pot experiments are consistent with previous works in field experiments (Sadras et al., 1989; Cabelguenne et al., 1999; Angadi and Entz, 2002) showing a conical root system. Nevertheless, a large genotypic variability in root length density was observed, especially in the first 0.40 m depth. The mean root length density in the top 1 m soil depth was significantly different between genotypes (Fig. 1 and Table 3). This value varied from 2.39 (Primasol) to 7.65 cm cm^{-3} (XRQ x PST5). Similar genotypic differences in root distribution were reported by Angadi and Entz (2002).

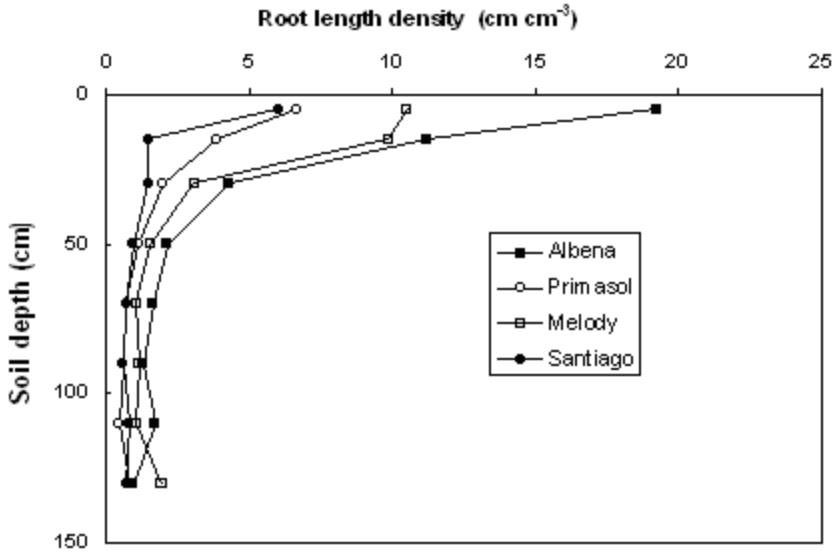

Fig. 1. Vertical distribution of root length density of four contrasted genotypes. Each point is the mean of 6 plants.

Table 3. Effective rooting depth and root length density. Values are average of 6 plants. Genotypes with the same letters did not differ significantly ($\alpha = 5\%$)

Genotype	Effective rooting depth (cm)	Mean root length density in the top 1 m soil depth (cm cm^{-3})
Peredovik	87 abc	5.10 abcd
Primasol	68 b	2.39 a
Albena	105 a	5.69 bcd
Vidoc	81 abc	6.17 cd
Santiago	71 bc	2.45 a
Melody	94 ac	4.52 abc
Prodisol	82 abc	2.91 ab
Sanbro	99 a	4.34 abc
VAQxPAR6	99 a	5.35 abcd
XRQxPST5	104 a	7.65 d

A large genotypic variability was observed for the effective rooting depth (Table 3). Values ranged from 68 cm (Primasol) to 105 cm (Albena). Three classes of genotypes were found, one with an effective rooting depth of below 71 cm, one with an effective rooting depth of over 99 cm and the last one with intermediate values. As all the genotypes were cultivated in identical soil columns, the differences could be attributed to genotypic plant characteristics. Nevertheless, it is worth noting that effective rooting depth in sunflower is also dependent on soil characteristics (Meinke et al., 1993). Different combinations of effective rooting depths and root length density were observed. Some genotypes with an effective rooting depth over 99 cm presented a high RLD as XRQxPST5 or a moderate one as Sanbro (Table 3). Other genotypes with an effective rooting depth of between 71 cm and 99 cm presented a low RLD like Prodisol or a high one such as Vidoc (Table 3).

Fraction of extracted soil water

The comparisons of the soil water depletion kinetics in experiments 1 to 4 revealed significant differences in the mean duration of pot desiccation between cultivars (data not shown). This resulted from differences in environmental conditions between experiments but also from differences in the initial developmental stages of the plants. But variability for soil water depletion duration did not have any influence on the

fraction of extracted soil water between the genotypes. The fraction of extracted soil water (EW) showed significant differences between genotypes (Table 4). Five classes of genotypes were found with a maximal difference of more than 10% between the extreme ones. For example, EW varied from 82.7% for the experimental hybrid VDQxOPB4 to 69.8 % for Peredovik.

Table 4. Fraction of extracted soil water. Values are the average for 5 or 6 plants.

Genotype	*Fraction of extracted soil water*[1] (%)
Peredovik	69.8 a
Primasol	71.3 abc
Albena	75.1 bcd
Vidoc	75.7 bcd
Santiago	71.4 abc
Melody	70.4 ab
Sanbro	75.8 cd
Prodisol	73.9 abcd
LG5660	73.1 abcd
Pegasol	73.9 abcd
VAQxPAR6	74.8 abcd
VDQxOPB4	82.6 e
VDQxPPR9	76.7 d
XRQxPPR9	70.5 ab
XRQxPST5	71.7 abcd

[1]Genotypes with the same letters did not differ significantly (α = 5%)

These classes were globally the same in the four experiments (Exp. 1 to 4). This result shows that the water extraction ability in sunflower was quite stable and it might be under genetic control. The stability and the heritability of EW should be studied in further experiments.

Genotypic extractable soil water

Significant differences in the indicator of the extractable soil water (EW_{gen}) were observed between genotypes (Fig. 2). Values ranged from 169, for Primasol, to 283 mm for Sanbro. This leads to a maximum difference of 114 mm between the genotypes studied corresponding to 28 - 38% of the amount of water used for a sunflower crop in West of Europe, which is about 300 to 400 mm. In this study, EW_{gen} was estimated for a reference soil with 0.13 mm mm^{-1} of available soil water (Ratliff et al., 1983). This range could be wider under field conditions. Indeed, the amount of available water for a crop depends either on plant or soil characteristics. For one cultivar of sunflower, Meinke et al. (1993) have found a total plant available water for the root profile ranging from 77 to 210 mm for a wide range of soil types.

The variability in EW_{gen} resulted from different combinations of effective rooting depths and fractions of extracted soil water. The lower EW_{gen} was observed in Primasol (Fig. 2), which combined a low effective rooting depth (Table 3) and a low fraction of extracted soil water (Table 4). Intermediate values of EW_{gen} were observed for low or high fraction of extracted soil water as for Melody and Prodisol (Fig. 2 and Table 4). Finally, the best performing genotype for water acquisition was Sanbro, which combined a high effective rooting depth (Table 3) and an intermediate fraction of extracted soil water (Table 4). These results are consistent with those of Angadi and Entz (2002) who attributed greater soil water depletion to deeper rooting depth. No genotype presented both a high effective rooting depth and a high fraction of extracted soil water. No correlation was found between EW_{gen} and the registration year of the genotypes (Table 2). That means that an unexplored source of variability could be used by the breeders to improve sunflower productivity.

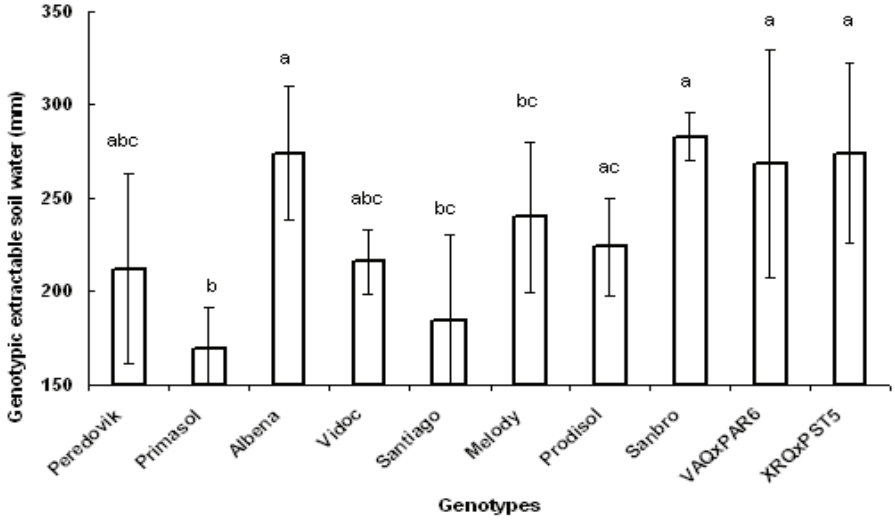

Fig. 2. Amount of extractable water of ten cultivars. Each point is the average of 6 plants. Vertical bars represent the standard deviation. Genotypes with the same letters did not differ significantly (α=5%)

CONCLUSIONS

This study showed a large genotypic variability for the root traits and the soil water extraction: root length density, effective rooting depth and fraction of extracted soil water. No correlation was found between EW_{gen} and the registration year of the genotypes, nor between effective rooting depth and fraction of extracted soil water. The modern genotypes are not better in soil water extraction than old ones. The effective rooting depth and the plant ability to extract soil water could be interesting targets for sunflower breeding programs. Ideotype with a deep root system and a low root density would be suitable under deep soil conditions. In contrast, ideotype with a small deep root system and a high root density would be suitable under shallow soil and limited water conditions.

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