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Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping

Florian Celette*, Rémi Gaudin, Christian Gary

INRA, UMR SYSTEM (INRA-CIRAD-SupAgro), Bât. 27, 2 place Viala, 34060 Montpellier Cedex 2, France

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ABSTRACT

The use of cover cropping is currently increasing in vineyards but its development remains hampered in Mediterranean regions because of the possibility of severe competition for resources. However, recent studies on intercropping in vineyards have shown that in some situations, water stress may not be greater than that prevailing in bare soil vineyards. Over a 4-year period, we studied the effects of introducing a cover crop in terms of temporal and spatial (i.e. row vs. inter-row) changes to the water regime of a Mediterranean vineyard. The experiments compared the water dynamics prevailing under three different treatments: a perennial cover crop, annual cover crop or the use of chemical weed control.

A compensatory growth of the grapevine root system was revealed, thus partly prevented direct competition for resources between it and the intercrop. The rooting of a permanent cover crop was deeper than that of an annual crop, with a higher root density. Consequently, the soil compartment dried by the cover crop was larger and the grapevine was forced to explore deeper soil layers. In the presence of a cover crop on the inter-row, the grapevine also concentrated its root system below the row and dried out this soil compartment more intensively. Overall, associating grapevine with a cover crop led to a spatial distinction of soil zones exploited by the two species. The present study provides evidence that this spatial shift mainly resulted from a temporal shift in the dynamics of resource uptake by the associated species. Indeed, cover crops began to take up water before grapevine budbreak and had almost completely dried out the soil compartment they explored before grapevine water uptake became significant. This led the grapevine to modify its rooting and explore other soil zones. This phenomenon is possible in deep soils and limits competition for water between the grapevine and cover crop. Such competition is also reduced because of better soil water replenishment during the winter in the presence of a cover crop. Nevertheless, our experiments showed that this additional water mainly benefited the intercrop and did not totally compensate for transpiration by the grass cover.

In conclusion, this work shows how cover cropping can spatially and temporally modify the water regime of a vineyard, and how grapevine can partially adapt to limit water competition under certain conditions. These findings provide a clearer understanding of the water dynamics prevailing in such a system, and an opportunity to model these dynamics.

1. Introduction

A variety of environmental benefits can be expected from cover crops in vineyards: soil protection, improvements to the physical and biological properties of soils, increased biodiversity, etc. However, in Mediterranean regions where water is the most limiting factor of crop production, vine growers remain concerned about introducing cover cropping in vineyards because of the strong competition for water resources they anticipate between the two crops.

Unlike many field and fruit crops which require a high level of water availability, vineyards need moderate water stress to produce the grape quality necessary for wine production (Dry and Loveys, 1998; Pellegrino et al., 2006). Thus water management in vineyards must avoid two excesses. If water resources are unlimited, vegetative development is luxuriant, but correlates to poor grape maturation and a high risk of fungal attacks (Zahavi et al., 2001) and requires repeated trimming and topping. Excessive water stress markedly restricts leaf growth (Gomez-del-Campo et al., 2002), particularly if it occurs before flowering (Wery, 2005), affecting the net assimilation rate (Pellegrino et al., 2005) and consequently yield and grape quality (Matthews and Anderson, 1989).

Under pedoclimatic conditions with high water availability, intercropping can be considered as a means of extracting soil water

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* Corresponding author. Tel.: +33 4 27 85 85 91; fax: +33 4 27 95 86 37.
E-mail address: celette@isara.fr (F. Celette).

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and generating the water stress targeted for grapevines. In regions experiencing a Mediterranean climate, summer rains are scarce and uneven, and current climate change models are predicting even drier conditions (Qadir et al., 2003). Irrigation has developed in the drier wine producing areas, but its use has been limited in regions producing wines of designated origin, and water resources for agriculture may be scarce in some areas. This context explains the lack of success with cover cropping in Mediterranean vineyards.

Nevertheless, studies of competition for water resources between grapevines and an intercrop have generated contradictory results. Some studies carried out under differing pedoclimatic conditions observed greater water stress affecting grapevines when they were grown with a cover crop (Maigre, 1996; Morlat, 1987; Moulis, 1994), whereas others showed that intercropped vineyards did not always exhibit higher water stress than those with bare soil (Celette et al., 2005; Chantelot et al., 2004). And indeed, cover cropping can affect several features of the crop–soil system. For example, a reduction in grapevine leaf area caused by early and moderate water stress contributes to reducing water consumption and limiting the water stress anticipated during grape growth. Cover cropping reduces runoff and increases water infiltration, which improves water filling of the soil profile in winter and makes more water available for both crops during their growth cycles (Battany and Grismer, 2000; Celette et al., 2005; Klik et al., 1998; Tournebize, 2001). In intercropped vineyards grown on deep soil, the grapevine root system can be redistributed and concentrated under the vine row and in deeper soil layers (Celette et al., 2005; Morlat and Jacquet, 2003). It is difficult to study the grapevine root system because it can be several meters deep (Trambouze, 1996). Several authors have considered (for practical reasons) that most grapevine roots are located within the first meter of soil (Champagnol, 1984; Morlat and Jacquet, 1993; Stevens and Nicholas, 1994). In any case, it is difficult to determine actual root depth and separate active and dead roots on a perennial crop such as grapevine (Radersma and Ong, 2004). For this reason, the dynamics and distribution of root activity in the soil profile should be described not only from observations of root distribution but also from observations of soil water content in different soil compartments (Nelson et al., 2006).

The present study aimed to describe the annual dynamics of the water balance in an intercropping system characterized by a marked contrast between woody and herbaceous perennial crops. A cover cropped vineyard structured in rows of grapevine and rows of cover crop was studied, focusing in particular on soil compartmentalization in terms of root development and water dynamics. For this purpose, experiments were carried out over a period of 4 years characterized by contrasting rainfall regimes, and different cover crop management systems were compared.

2. Material and methods

2.1. Experimental set-up and climatic conditions

The experiments were carried out from 2003 to 2006 on a 1.5 ha vineyard near Montpellier in the south of France (43°32′N–3°50′E). The vines (*Vitis vinifera* L. cv. Aranel grafted on Fercal) had been planted in 1997 in rows (2.5 m × 1.2 m, i.e. 3333 plants/ha) oriented WNW-ESE (Fig. 1). Before planting, the soil was rippered to a depth of 0.8 m and then ploughed to a depth of 0.3–0.4 m each year during the first 3 years after plantation. Soil was a deep, calcaric Fluvisol (FAO classification). It was a homogenous clay loam (34% clay, 35% silt and 31% sand) containing less than 10% of coarse elements. It was little susceptible to soil swelling. The field slope was about 2–3% in the upper part and less than 1% at the bottom of the field. The soil bulk density of the first 3 m, measured by gamma-densimetry every 20 cm, varied from about 1.6 in the upper soil layers to 1.7 in deeper layers, so that soil porosity was about 40%.

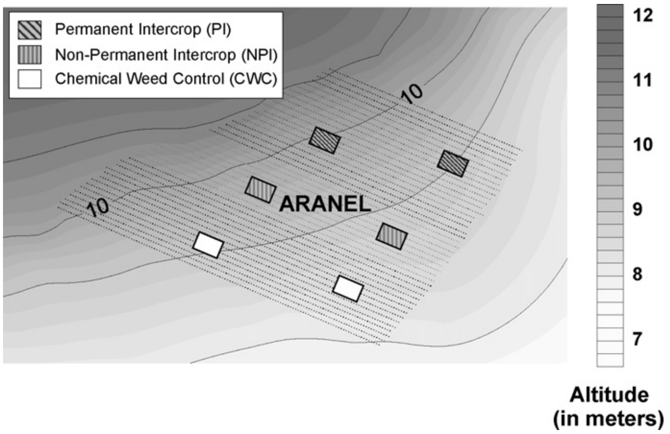

Fig. 1. Map of the experimental set-up. Three treatments were studied: one with a permanent intercrop (PI), another with a non-permanent intercrop (NPI) and a third with chemical weed control (CWC). Two plots were defined per treatment.

In 2002, the three treatments were (Fig. 1): (1) a perennial cover crop in the inter-rows, comprising a mixture of tall fescue (*Festuca arundinacea* L.) and English ryegrass (*Lolium perenne* L.) (PI), (2) an annual cover crop of barley (*Hordeum vulgare* L.) sown every autumn in the inter-rows and destroyed by surface tillage just after grapevine flowering (mid-June) (NPI), and (3) full chemical weed control (CWC). Cover crops rows were 1.5 m wide (60% of the soil surface area) and chemical weed control was applied under the grapevine rows. For each treatment, two sets of 180 grapevines (6 rows × 30 plants) were identified in two blocks that differed in terms of their slope and position in the field.

The climate was Mediterranean, with an average rainfall from 700 to 750 mm per year, and a water deficit (ETP–rainfall) of 150–200 m per year. The water deficit was highest during the grapevine growth cycle (ranging from 400 to 680 mm between April and September in different years). In 2003, rainfall was close to average except in the autumn (1200 mm over the year), and temperatures were higher than average, particularly during the summer (Fig. 2). In 2004, rainfall and temperatures were close to average. In 2005, the winter was dry and generated an early water deficit that was subsequently amplified by a dry summer. In 2006, rainfall was almost nil between January and harvest, which generated a marked water deficit (about 800 mm).

Data from another experiment are also used in this paper to evaluate the relation between the root density of the two species. This experiment was carried out from 2002 to 2003 on a different vineyard located at a distance of less than 50 km from the vineyard studied in this article, and was described in Celette et al. (2005). Vines were 10-year-old *V. vinifera* L. cv Sauvignon blanc grafted on SO4 and planted to a similar density. As in the present experiment, soil was a deep and homogeneous loamy-clay calcaric Fluvisol. The intercrop (tall fescue) was sown in 1997, 5 years before the measurements, and thus behaved like a perennial cover at the time of experiment. The climate was also of a Mediterranean type and very similar to that described above.

2.2. Soil water balance

A weather station was installed on the experimental plot. It measured air temperature, wind speed (at a height of 2 m), air humidity and rainfall. The data were recorded on a CR10X data logger (Campbell Sci. Inc., USA). Potential evapotranspiration (PET)

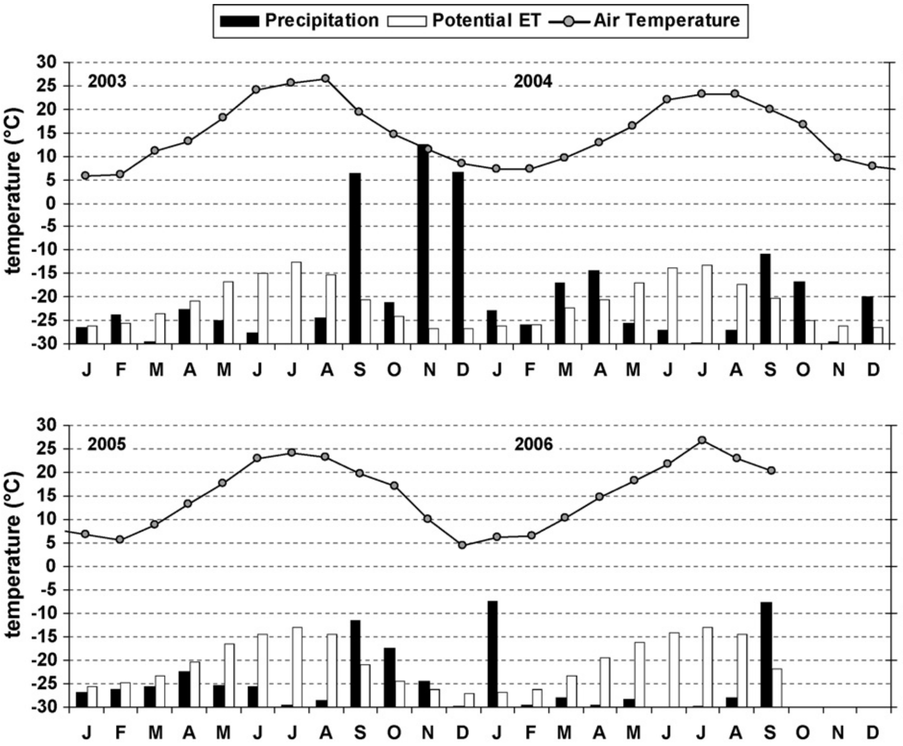

Fig. 2. Evolution of climate conditions affecting the experimental plot between 2003 and 2006. Rainfall and potential evapotranspiration (PET) are represented (histograms), as are mean air temperatures (line).

was calculated using the Penman–Monteith equation (Allen et al., 1998).

The soil water content was measured with neutron probes (CPN 503 DR). On each plot, three 3-m aluminum tubes were placed 2.4 m apart along the grapevine row, and three others in the axis of the inter-row. One 5-m tube was installed on each plot subjected to the PI and CWC treatments. Measurements were performed every 0.2 m to a depth of 1.6 m, and then every 0.4 m.

Total transpirable soil water (TTSW) was estimated from the soil water content measured up to a depth of 4.0 m, insofar as no changes to water content were detected below that level. For each soil layer, the maximum water content ($W_{\max}$) measured during the 2002–2003 and 2003–2004 winters after heavy rains were considered to be close to field capacity. For each soil layer, the minimum water content ($W_{\min}$) was the lowest level measured over a fixed period of time. This did not necessarily correspond to the wilting point, as applied by other authors (Lacape et al., 1998; Pellegrino et al., 2004; Sinclair and Ludlow, 1986). A specific TTSW was estimated for each cover crop from the $W_{\min}$ observed at the end of the grass growth period and for the different soil layers explored by the grass root system.

The soil water potential was monitored weekly using simple water tensiometers (SDEC, France) from grapevine budbreak in the PI and CWC plots. Tubes were situated close to the neutron probe tube (at a distance of 2 m) in the inter-row to monitor the soil matrix potential at depths of 2.5 and 2.8 m and thus evaluate any vertical direction of water fluxes at the bottom of the soil profile (Trambouze, 1996).

Runoff was measured in situ throughout the year in the PI and CWC plots. A sample area of soil surface (about 15 m^2), located near the neutron probe tubes, was isolated using a vertical strip of rigid rubber, and the outlet was connected to a tipping counter (UGT GmbH, Germany). One liter bucket tippings were recorded on the CR10X data logger every 15 min. This system was dimensioned to measure runoff fluxes of up to 15–20 mm h^{-1}; during some periods of heavy rain (more than 100 mm per day), the fluxes thus measured were eliminated if they were higher than these threshold values. A response curve of the ratio of surface runoff to rain intensity was calculated as in the SWAT (Soil and Water Assessment Tool) model (Chanasyk et al., 2003; Jayakrishnan et al., 2005; Tripathi et al., 2003, 2006). The curve number (CN) coefficient was optimized from a dataset concerning about 100 periods of rainfall between spring 2005 and autumn 2006. The CN is an empirical parameter that varies as a function of soil surface properties and rainfall over the preceding 5 days (Chanasyk et al., 2003; Mapfumo et al., 2004; USDA, 2004b).

Soil hydrodynamic properties were estimated using the Wind method (Bruckler et al., 2002; Tamari et al., 1993). Undisturbed soil cylinders were harvested at depths of 0.5 and 1.2 m during the winter of 2004. These soil samples were then submitted to progressive air evaporation under controlled laboratory conditions. The total sample mass was monitored continuously, as was the soil matrix potential to various depths of the soil cylinder, using micro-tensiometers.

The retention curve ($h(\theta)$) was established from field tensiometric and neutronic measurements. It was calculated at the same soil depths as the $K(h)$ curve and was relatively comparable to the value obtained from laboratory measurements. Both curves were optimized using the Van Genuchten formulation (1980). Because soil textures were relatively similar from one treatment to another, and no significant differences were observed between the PI and CWC treatments regarding optimized parameters, it was finally considered that the physical properties of soil were the same under all treatments. The resulting parameters in the Van Genuchten formulation were: $\alpha = 6.263$, $l = 0.5$, $n = 1.200$, $m = 0.167$, $\theta_r = 0.083\ \text{m}^3\ \text{m}^{-3}$, $\theta_s = 0.385\ \text{m}^3\ \text{m}^{-3}$.

Finally, water depth was monitored using two piezometers installed at the lowest and highest points of the experimental site.

2.3. Root distribution

The spatial distribution of the root system of each species was described in situ using the trench profile method (Van Noordwijk et al., 2000). One trench per experimental plot (two per treatment) was dug in March 2004 and March 2006, this period of the year being chosen to avoid harm to the grapevines. NPI treatment trenches were dug after cover crop destruction in order to not damage the sowing of barley. Roots were counted on the vertical sides of the trench using a 1 m × 1 m grid within 0.1 m × 0.1 m cells. This grid was applied on the observation wall after roughening of the soil surface with a spike. Three counts were performed in each trench: one in the middle of the inter-row, another approximately 0.3 m from the row on a wall parallel to it and one on a wall perpendicular to the vine row. Vine and fescue roots were differentiated on the basis of color and shape. Exposed roots were classified by diameter as follows: <2 and > 2 mm. Finally, the trench wall was roughened down to the bottom of the trench (1.5–1.7 m deep) in order to detect any deep roots.

Root impact counts were transformed into root length density using the method developed by Chopart and Siband (1999) on maize. Three 0.1 m cubic soil samples were removed from each trench wall. Measurements produced no evidence of a preferential direction for grapevine root growth, so that a more appropriate equation was:

$$\mathrm{RLD} = 2\mathrm{NI} \tag{a}$$

With RLD = root length density (cm cm^{-3} of soil),
NI = number of root impacts observed (m^{-2}).

As previously seen in maize (Chopart and Siband, 1999), intercrop root systems grew according to a planar anisotropy, revealed using the following equation:

$$\mathrm{RLD} = X \cdot \mathrm{NI} \tag{b}$$

With a calculated X factor of about 3 for barley and 5 for tall fescue.

The same methods were used on an independent data set collected during another, similar experiment (Celette et al., 2005).

Finally, the zones exploited by root systems were evaluated using neutronic monitoring and TTSW, determining depth where soil moisture variations were significant during the year, as proposed by other authors (Nelson et al., 2006; Sinclair and Ludlow, 1986).

3. Results

3.1. Contrasted growth dynamics of grapevine and cover crop

The time-course of shoot biomass production differed markedly between the different species (data not presented) (Celette, 2007). The grapevine grew mainly during the spring and summer seasons, with an initial growth peak in May during shoot formation and a second peak during berry development. The permanent cover crop (PI treatment) exhibited earlier growth peaks: one in early autumn as a result of frequent periods of rainfall at that time, and another in early spring when temperatures rose and soil resources were abundant. The permanent cover crop growth rate remained high until late spring. Barley (NPI treatment) displayed comparable growth dynamics, although the autumn growth peak was lower and the spring growth peak higher. This behavior was strongly dependent on conditions during emergence: in 2005–2006, the poor emergence conditions led to lower barley growth rates whereas the permanent cover crop yield was relatively normal (2.0 and 3.2 t ha^{-1}, respectively). In 2004–2005, dry conditions during the spring also led to low yearly yields of cover crops that affected both intercropped treatments (1.8 t ha^{-1} for NPI and 1.6 t ha^{-1} for PI). The yearly yield of cover crop biomass was low in all cases (from 1.5 to 3.5 t ha^{-1}) when compared to those observed under more favorable conditions.

3.2. Distribution of grapevine and cover crop root systems

In the context of the bare soil treatment, the root system was distributed homogeneously under grapevine rows and inter-rows, within the first meter of soil (Fig. 3). The only significant difference was observed regarding lower root length density (RLD) in the first 0.1 m of the inter-row in 2004. The RLD observed ranged from 0.01 to 0.1 cm cm^{-3}; because there was no significant differ-

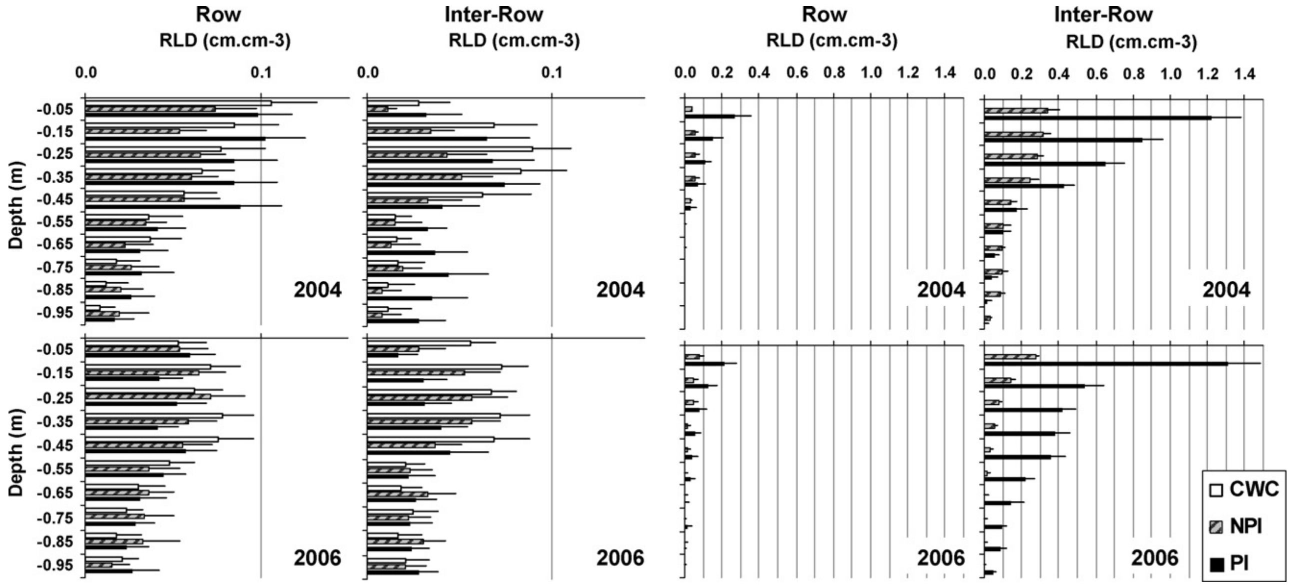

Fig. 3. Grapevine (left) and intercrop (right) RLD (root length density) observed at various depths as a function of studied treatments. RLD were observed in 2004 and 2006 and below the row vs. inter-row. The represented errors are 5% confident intervals calculated with a Student law.

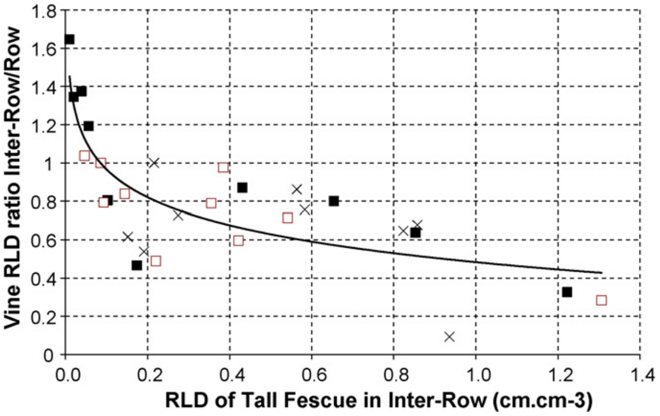

Fig. 4. Ratio between grapevine RLD (root length density) below the inter-row to those below the row, and the RLD of tall fescue below the inter-row under the PI treatment. Filled squares (■) represent mean observations for 2004 and open squares those for 2006 with the permanent intercrop treatment. Crosses (×) indicate observations from independent datasets generated in 2002 (Celette et al., 2005). Logarithmic regression was established for the three datasets.

ence between the 2 years of observation, it was considered that development of the root system had attained a steady state at the beginning of the experiments, i.e. 7 years after planting.

The root systems of annual and perennial intercrops preferentially explored soil layers beneath the inter-row (Fig. 3). The rooting of annuals changed over the years, the RLD being lower in 2006 (from 0 to 0.3 cm cm^{-3}) than in 2004 (from 0.05 to 0.4 cm cm^{-3}) when emergence was better. Barley RLD values were significantly ($p < 0.05$) higher in 2004 than in 2006 in soil layers at depths from 0.1 to 0.8 m. The rooting of perennials displayed more consistent features over the years. Most roots were located within the first 0.50 m of soil (85–100% of roots observed within the first meter), beneath the row and inter-row. The perennial cover crop RLD was higher (from 0.1 to 1.3 cm cm^{-3}) than grapevine root density, to a depth of 0.6 m in 2004 and 0.9 m in 2006. This increase over time in grass root depth correlated with a reduction in grapevine root density.

The grapevine root system distribution was altered with both annual and perennial intercrops. The RLD of grapevine with annual cover crop was similar below the row to the one of a grapevine with bare soil, but lower beneath the inter-row. This difference was significant ($p < 0.05$) (50% reduction) in 2004, but not always in 2006, despite a notable decrease. In 2004, the RLD of grapevine associated to a perennial cover crop was higher than the RLD of grapevine with bare soil, down to a depth of 0.5 m ($p < 0.1$) and below 0.5 m beneath the inter-row. By contrast, it was lower ($p < 0.05$) beneath the inter-row to a depth of 0.4 m. In 2006, RLD of a grapevine with a perennial cover crop were lower than the RLD of a grapevine with bare soil, down to a depth of 0.5 m under both the row and inter-row.

Overall, the higher the tall fescue RLD beneath the inter-row, the lower was the ratio of inter-row to row grapevine RLD (Fig. 4). Above a threshold RLD value for tall fescue (around 0.1 cm cm^{-3}), the grapevine concentrated its root system under the row. Data from an independent dataset (Celette et al., 2005) fitted the same logarithmic relationship ($R^2 = 0.63^{***}$ for the two datasets). Such a correlation was not observed with the annual intercrop that did not develop a permanent root system throughout the year.

Analysis of the dynamics of soil water content profiles provided a further means of characterizing root system dynamics. Under all treatments, water was taken up at lower levels during 2005–2006 than during 2003–2004 (Fig. 5), which was certainly linked to the poor replenishment of soil water profiles during the winters of 2005 and 2006. From 2003–2004 to 2005–2006, grapevine water use depth increased from 3.0 to 3.6 m under bare soil and from 3.6 to 4.0 m under a permanent intercrop, whereas it was no deeper than 2.8 m under an annual intercrop during both periods.

Soil water content significantly decreased between the beginning (end of winter) and end (mid-June) of the grass growth period, down to depths of 1.5 and 1.2 m under perennial and annual intercrops, respectively, with few differences between years (Fig. 5). These depths were thus considered as the maximum depths of effective soil water use by the root systems of the two intercrops.

3.3. *Estimation of water reserves available to the two crops*

$W_{\max}$ was considered to remain constant throughout the experiment as it is solely dependent on soil texture; indeed, this value did not differ between treatments (Fig. 5). By contrast, $W_{\min}$ values result from the properties of both soil and root systems. They were significantly ($p < 0.05$) lower with intercrops than under bare soil, down to a depth of 0.6 m and 1.2 m with annual and perennial intercrops, respectively. During the 2003–2004 period, $W_{\min}$ values at depths of between 0.8 and 3.0 m were higher under an annual intercrop than with the other two treatments, when $W_{\min}$ values were similar. During the 2005–2006 period, $W_{\min}$ values at 1.6–2.5 m were lower under a perennial intercrop than with the other two treatments, whereas $W_{\min}$ values were highest throughout the soil profile under an annual intercrop. Over the 4-year period, water content at greater depths changed more under a permanent intercrop than under bare soil, yet not significantly (20 mm between depths of 3.5 and 4 m with the INT treatment vs. 11 mm with the CWC treatment: $p < 0.1$).

TTSW values were lowest under the annual intercrop and increased only slightly, from 296 mm in 2003–2004 to 303 mm in 2005–2006. TTSW values were similar under the perennial intercrop and bare soil in 2003–2004 (330 and 335 mm, respectively), but then increased more rapidly under the former in 2005–2006 (369 and 357 mm, respectively), because of an improved exploitation of water resources throughout the soil profile (Fig. 5).

Under a perennial intercrop, $W_{\min}$ values decreased during the 2005–2006 drought period at depths of between 0.6 and 1.5 m (Fig. 6), and the grass TTSW increased proportionally (from 82 mm in 2003–2004 to 116 mm in 2005–2006). By contrast, under an annual intercrop, grass TTSW values remained stable over the two periods (57 mm then 59 mm).

3.4. *Cover cropping and water uptake*

An analysis of root dynamics in the soil profile enabled the identification of four soil compartments that differentiated the dynamics prevailing under the row (A and C) from those under the inter-row (B and D), at the surface (A and B) and at depth (C and D). The limit between the surface and deep compartments was fixed at 1.5 m, this being identified as the maximum depth of effective soil water use by the root systems of the two intercrops. Compartment B was the only one to be used by intercrops for water uptake.

In compartment B (surface layer under the inter-row), monthly changes to the soil water content during the winter season did not differ between treatments; at that period, grass transpiration was compensated by better infiltration. In early spring, compartment B dried earlier and more rapidly under an intercrop than under bare soil (Fig. 7). The water uptake of grapevine was still negligible at that time, and the grass transpiration rate was higher than the bare soil evaporation rate. From May until the first rains of autumn, compartment B always remained drier under a perennial intercrop than under other treatments by 4 ± 1 cm^3 cm^{-3} in 2003 and 5 ± 1 cm^3 cm^{-3} from 2004 to 2006. Under an annual cover crop, the drop in soil water content was significantly greater than

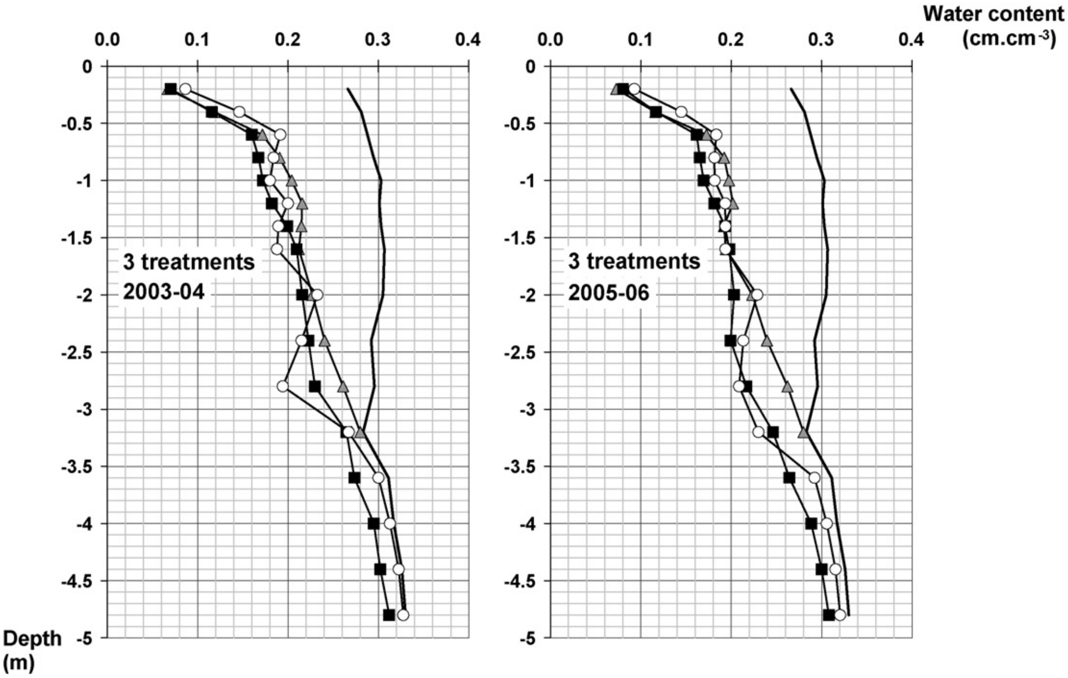

Fig. 5. $W_{\min}$ for each treatment studied: CWC (Chemical Weed Control: ○), NPI (Non Permanent Intercrop: ▲) and PI (Permanent Intercrop: ■) for the periods 2003–2004 and 2005–2006. The same $W_{\max}$ (continuous line) is considered for all treatments.

under bare soil only in April (Fig. 7). After the annual intercrop had been destroyed by surface tilling, the soil water content decreased less rapidly in compartment B, as transpiration stopped and soil evaporation was limited by a mulch effect.

In compartment A (surface layer under the row), changes to soil water content did not differ between treatments during the growth period of cover crops. In the summer, compartment A dried out more in the presence of a permanent intercrop (PI) than under other treatments (Fig. 7); this resulted from grapevine transpiration as the cover crops were no more active at that time. Moreover, this drying was observed late during the crop cycle when the intercrop was almost dry (early summer); it occurred earlier in the treatment with a permanent intercrop (PI) than with a bare inter-row (CWC). Under bare soil, the two surface compartments exhibited similar changes in soil water content.

Soil water content decreased at an early stage in deep compartments (C and D) (Fig. 7). There was little difference between treatments. The compartment under the row (C) dried slightly more rapidly in the summer, particularly with intercropped treatments. In these deep compartments, reductions in soil water content depended on the water regime prevailing during different years. They were the least rapid in 2004 after a satisfactory winter replenishment of soil water reserves but more rapid in 2006 after a dry winter and spring (less than 50 mm of rain between January and June 2006).

3.5. Cover cropping and runoff

CN values were optimized relative to measured surface runoff. CN values differed between treatments: 91 for bare soil and 74 for a cover crop. If reference was made to other studies, then the CWC treatment corresponded to bare soil with poor water conductivity and poor to medium hydraulic conditions. A value of 74 nearly corresponded to a meadow with a cover rate of more than 50% and poor soil water conductivity (USDA, 2004a). Based on the response curve of the surface runoff to daily rainfall ratio (Fig. 8), a runoff threshold could be estimated at 6 mm of daily rain for bare soil and 25 mm for a cover crop. Correlations between observed and calcu-

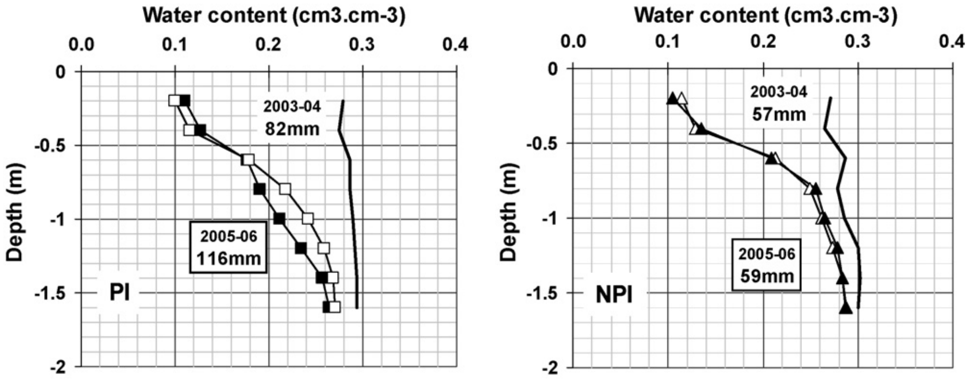

Fig. 6. $W_{\min}$ and $W_{\max}$ values of the soil compartment explored by the intercrop root system during the periods 2003–2004 (open dots) and 2005–2006 (full dots). $W_{\min}$ were observed at the beginning of the dry period (mid-June).

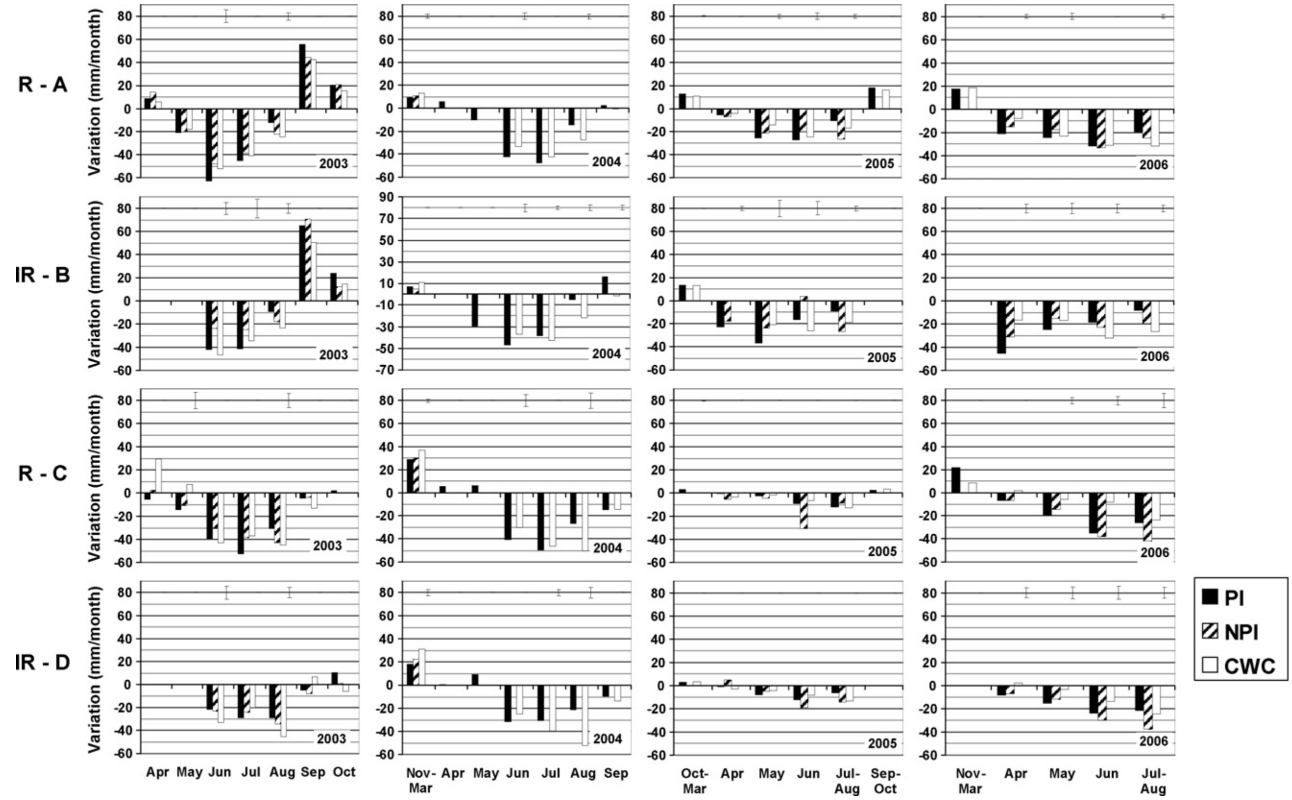

Fig. 7. Water stock variations in different soil compartments defined as a function of the treatments studied. Bars in the upper section of graphs represent the smallest significant difference between two treatments during the period concerned. This difference was calculated using a Newman–Keuls test with $\alpha = 0.05$. Some data were missing for 2004 under the NPI treatment, which explains why there are no bars for this treatment from April to September of that year. A, B, C and D correspond to the various compartments defined and R and IR means Row and Inter-Row, respectively.

lated surface runoff values were good for both treatments (CWC: $R^2 = 0.98^{***}$; PI: $R^2 = 0.96^{***}$). The Relative Root Mean Square Error (RRMSE) calculated for days when some rainfall occurred was low (CWC: RRMSE = 0.15; PI: RRMSE = 0.16).

3.6. *Possible contribution of drainage and capillary water transfers*

During the autumn–winter period, rainfall was generally abundant (Fig. 2). A simple water balance (rain–PET–runoff) calculated for the period October 2003–March 2004 was positive (200 mm under bare soil) to highly positive (more than 400 mm under a cover crop). Such conditions could lead to drainage at the bottom of the 3-m soil profile. This was confirmed by the analysis of soil water profiles. Under cover cropped treatments, the water content was higher of about 90 mm in December 2003 than in March 2004 throughout the soil profile. Outside the period of grapevine activity, water loss in deep soil layers could be explained by drainage, rather than by soil evaporation or grass transpiration. By contrast, under bare soil, there was less change (about 10 mm) in the soil water content from December 2003 to March 2004 and drainage certainly did not occur in deep soil layers. During the winters of 2004–2005 and 2005–2006, the water balance was negative under bare soil and slightly positive under a cover crop, and deep soil compartments were not fully replenished; there were few chances of deep drainage.

The matrix potential gradients measured at depths of between 2.5 and 2.8 m were every year, slightly negative (on average from −8 to −30 kPa) at the beginning of the grapevine cycle (possible deep drainage) and slightly positive (from 0 to 8 kPa) in the sum-

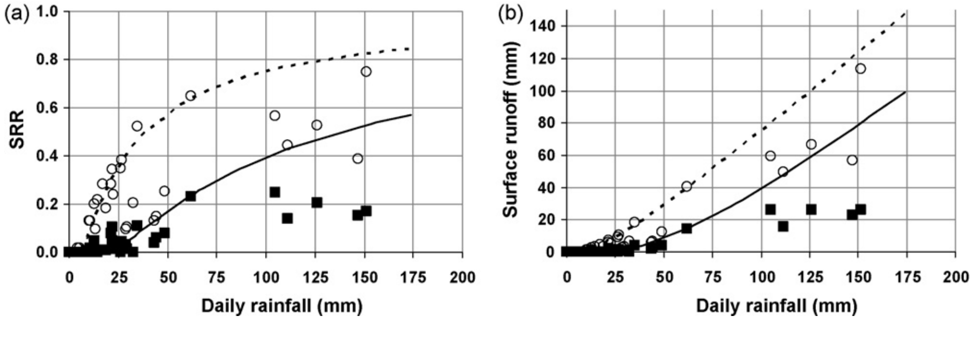

Fig. 8. Surface Runoff Ratio (SRR) (a) and amount of surface runoff (mm) observed at a daily rate (b) in relation to daily precipitation on the experimental plots. Dots represent values observed with the CWC (○) and PI (■) treatments. Links were established between the daily intensity of rainfall and SRR regarding the CWC treatment (dotted line) and the PI treatment (continuous line).

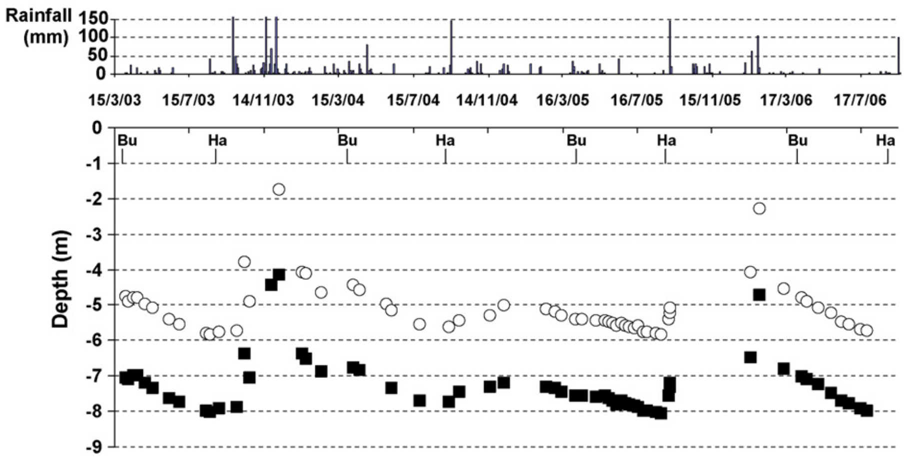

Fig. 9. Time course of water table depth in the lower (○) and upper (■) parts of the experimental plot. The upper graph represents daily rainfall during this period. Budbreak (Bu) and Harvest (Ha) are marked in the upper part of the lower graph.

mer under a perennial cover crop (possible capillary rise). However, the hydraulic conductivity calculated for deep soil compartments was very low (from 10^{-11} to 10^{-12} mm j^{-1}) whatever the treatment. Because the matrix potential was limited, water flow by capillary rise was certainly very limited (<10^{-8} mm j^{-1}).

Most of the time, the water table was too deep (at about 5 and 7 m in the lower and upper parts of the field, respectively) to interact with the water balance with respect to low soil water conductivity (Fig. 9). Nevertheless, it rose closer to the soil surface during the heavy rains of December 2003 when it may have contributed to replenishing the soil water profile.

4. Discussion

4.1. Improved winter replenishment of the water profile under a cover crop

These findings confirm the value of cover cropping to ensuring an improved replenishment of the soil water profile (Battany and Grismer, 2000; Celette et al., 2005; Klik et al., 1998). This is related to a reduction in runoff and the resulting improvement in water infiltration. Such a reduction in runoff can be correlated to the area of soil covered (Battany and Grismer, 2000). It is particularly significant in regions with a Mediterranean climate that experience heavy storms (Leonard and Andrieux, 1998; Wassenaar et al., 2005). When soil hydraulic conductivity is low, as in the present case, the efficiency of rainfall (infiltration/runoff ratio) is low (Jayakrishnan et al., 2005; Mapfumo et al., 2004) but this can be improved by cover cropping, as has been observed in fallow land (Moret et al., 2006). During the present study, this additional water infiltration during the winter was estimated at 0–60 mm, depending on the year and rainfall.

The improved replenishment of the soil water profile observed under a perennial cover crop often compensates for later additional water uptake due to grass transpiration (Celette et al., 2005). This is particularly true as a cover crop may suffer from water stress that limits both growth and transpiration. Indeed, with both barley and tall fescue, it may represent no more than 20–30% of biomass production monitored under conditions of forage production (Cantero-Martinez et al., 2003; Lemaire and Salette, 1981; Norton et al., 2006; Volaire et al., 1998). During our experiment, the additional water infiltration in winter accounted for up to 0–80% of the additional water uptake observed in the presence of a permanent intercrop.

Nevertheless, these additional water resources are mainly available to the cover crop because it starts its vegetative cycle earlier than grapevine (Celette et al., 2005) and then obtains an advantage over grapevine in the competition for water (Willey, 1990). However, under soil and climate conditions that permit a satisfactory winter replenishment of the soil water profile – even under bare soil – there is no benefit with cover cropping and subsequent competition for water may be more severe (Monteiro and Lopes, 2007).

4.2. The root plasticity of grapevine limits competition for water resources

The grapevine root system is plastic and highly sensitive to the soil water content and temperature conditions (Guix, 2005). Its distribution in different soil compartments changes with the introduction of cover cropping. Because of the time shift between the two crop cycles, the cover crop takes precedence in terms of water uptake from the surface soil compartment beneath the inter-row. This is particularly marked with tall fescue because it develops a high root density. As a result, the grapevine root system tends to be concentrated under the row where cover crop root density is low. This behavior was observed previously not only in cover cropped vineyards (Morlat and Jacquet, 2003), but also under other intercropping systems such as agroforestry (Fetene, 2003; Lehmann et al., 1998; Smith et al., 1999). This redistribution of the root system of the species suffering most from competition for resources has been named compensatory growth (Miller, 1986). Root redistribution is not only horizontal but also vertical, as revealed by the analysis of soil water profiles, thus proving that a cover cropped grapevine tends to take up water from deeper soil layers. This deeper uptake actually occurs every time the surface soil compartments become drier, because of dry climatic conditions or grass transpiration (Mulia and Dupraz, 2006). However, this kind of acclimation has been observed in deep soils. On a shallow soil, early drying of the soil compartment beneath the inter-row inhibits root growth of the woody species (Odhiambo et al., 2001).

4.3. Dynamics of water sharing within the intercropping system

The dynamics of water resource sharing between grapevine and a cover crop is strongly determined by the time shift between the two crop cycles. Because of their earlier development, grasses take up water in the surface compartment beneath the inter-row where they concentrate their root systems before grapevine budbreak. By the beginning of the dry summer season (June), the foliage of a perennial cover crop has become senescent and an annual cover crop has been destroyed, so that the grapevine transpires more and mainly takes up water under the row.

A perennial intercrop makes better use of soil water resources than an annual one; water is taken up at lower levels (down to 1.5 and 1.2 m, respectively) and more intensively (up to twice as much water taken up by a perennial intercrop than by an annual intercrop over a year). This is due both to the intrinsic characteristics of the two crop species (tall fescue and barley) and to their respective management. An annual intercrop needs to rebuild its root system every year whereas a perennial intercrop can develop and densify its root system over the years. The depth of water uptake by cover crops may not correspond to their actual root depth if capillary rise from lower soil layers has contributed to supplies.

This is also true for the grapevine root system. The depth of water uptake that was observed during the present study (more than 4.0 m) was greater than that previously reported (around 2.5 m) in comparable vineyards with a bare inter-row (Koundouras et al., 1999; Pellegrino et al., 2004; Trambouze et al., 1998). Trambouze (1996) observed that soil layers between 1.8 and 2.7 m depth represented less than 10% of total evapotranspiration. Under the bare soil treatment in this study, soil layers below 1.8 m represented 25% of total water uptake during the 2003–2004 period and 30% during the 2005–2006 period. The same deep soil layers represented less than 20% and from 25%–30% of total water uptake over these years, with annual and perennial cover crops, respectively.

Grapevine takes up water from the entire soil profile, as from budbreak (Trambouze, 1996). The contribution of deep soil layers increases when the surface soil layer is dry (Morlat and Jacquet, 1993). In our conditions, soil layers below a depth of 2.7 m contributed 5–10% of total water uptake, probably more by direct root uptake than by capillary rises due to the very low hydraulic conductivity. Even though these values are quantitatively low, various authors have emphasized the significance of this contribution to the survival of grapevine during periods of severe drought (Champagnol, 1984; Morlat et al., 1992; Seguin, 1972; Smart and Coombe, 1983; Stevens et al., 1995).

5. Conclusion

A clearer understanding of interactions within the grapevine–cover crop–soil system is possible if (i) the time shift between the two crop cycles, (ii) the spatial (i.e. row vs. inter-row) difference in soil exploration by the two root systems and (iii) the reduction of runoff and increase in infiltration in cover cropped soils, are considered. An intercrop takes up water from the soil compartment located beneath the inter-row, the depth of which differs as a function of species, environmental conditions and cultivation techniques. The grapevine can take up water from all soil compartments and at deeper soil layers than a cover crop. However, due to earlier development of the cover crop, it mainly takes up water under the row and from deep soil compartments, and partially concentrates the distribution of its root system in these soil volumes. The benefits of grapevine root system plasticity depend on the competitiveness of the intercrop and on soil depth. Redistribution of the grapevine root system may be relatively rapid, as evidenced by this short-term experiment over a period of only 4 years. A reduction in runoff under cover crops was observed and partly compensated (up to 80% in this situation) for the extra water loss due to their transpiration, in a region where runoff is a significant water flux. However, it cannot totally replenish the soil profile during winter. This was particularly true in this situation as the soil was deep, but would probably not be the case in a shallower soil.

This framework opens the way to modeling the water balance in a grapevine–cover crop–soil system. As a minimum, such a model needs to identify the specific soil compartment that feeds the cover crop (compartment B in the present research). This framework provides guidelines to identify specific policies regarding cover cropping in Mediterranean regions that would meet both productive and environmental objectives.

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