

THERMAL PROPERTIES IN RELATION TO SOIL WATER STATUS IN SLOPING VINEYARD

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Summary. Knowledge of thermal properties of soil helps in estimating heat fluxes as an important component of heat balance. The research was conducted to evaluate spatial distribution of the soil thermal properties (thermal conductivity, heat capacity and thermal diffusivity) in relation to soil wetness and bulk density in a sloping vineyard under two management systems: cultivated (C) and grass-covered (G) soil. Soil samples were taken in spring and autumn in places corresponding to upper rut (UR), inter-rut (IR) and lower rut (LR) areas, and following determination of current water content they were adjusted to the wetness statuses: dry, field capacity (pF 2.0) and saturated (pF 0). Current soil water content (at sampling) was near field capacity in spring and considerably lower in autumn. Soil water content and bulk density at each soil wetness status, together with soil temperature and texture data, were used for determination of the thermal properties. Thermal conductivity was calculated by the physical-statistical model of Usowicz, and heat capacity – with formulae of de Vries, and thermal diffusivity from the ratio of thermal conductivity and heat capacity. Thermal conductivity and heat capacity increased with increasing water content. Increase of thermal conductivity was greater up to field water capacity than at higher water contents, whereas that of heat capacity was uniform in the whole range of water contents studied. However, thermal diffusivity reached its maximum at and near field water capacity. In autumn, the thermal diffusivity at current water content was slightly lower than at field water capacity, despite appreciably lower current soil water content. This was a resultant effect of water content and bulk density on diffusivity. At both management systems the courses of thermal diffusivity as affected by soil water statuses were similar. The whole range of water status allowed determining possible values of the soil thermal properties. The dispersion of thermal conductivity and heat capacity was highest and lowest at current and dry wetness statuses, respectively. In spring, the dispersion was lower in inter-rut area than under the ruts. Irrespective of the management system, dispersion of the thermal properties under the ruts was lower in autumn than in spring, whereas in the inter-rut area the inverse was true, likely due to respective effects of tillage operations and traffic during growing season. Our results emphasize the need to include spatial variability of the thermal properties within inter-row area to improve accuracy in evaluating the energy balance in a vineyard.

Key words: soil thermal properties, water status, vineyard, management

INTRODUCTION

Thermal properties affect energy partitioning at ground surface and the resulting soil temperature distribution influences many soil processes and plant growth. The energy balance at the soil surface, where the radiation energy transforms into other forms of energy, is described by:

$$R_n = G + H_s + LE \quad (1)$$

where:

R_n – net radiation,

G – soil heat flux,

H_s – sensible heat flux,

LE – latent heat flux;

all heat fluxes are in W m^{-2} .

Heat flux density in a homogeneous soil medium is directly proportional to temperature gradient according to the equation:

$$G = -\lambda \frac{\partial T}{\partial z} \quad (2)$$

where:

λ – thermal conductivity of soil in $\text{W m}^{-1} \text{K}^{-1}$,

$\frac{\partial T}{\partial z}$ – gradient of temperature (T in K) along axis z (z in m).

Under unsteady state heat flux is described by the continuity equation to obtain time-dependent differential equation:

$$C_v \frac{\partial T}{\partial t} = -\frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) \quad (3)$$

where:

C_v – heat capacity of soil in $\text{J m}^{-3} \text{K}^{-1}$,

t – time in s.

The values of λ and C_v in a homogeneous and isotropic medium are constant. The ratio of thermal conductivity and volumetric heat capacity C_v is called coefficient of thermal diffusivity α ($\text{m}^2 \text{s}^{-1}$):

$$\alpha = \frac{\lambda}{C_v} \quad (4)$$

The soil heat flux density depends on the thermal conductivity that is largely influenced by soil water or air-filled porosity and bulk density [Ochsner *et al.* 2001, Usowicz *et al.* 2006a, Murray and Verhoef 2007]. The thermal conductivity may vary by several times within a range of field soil water contents [Sauer *et al.* 2003] and therefore the variations are most pronounced in regions with considerable wetting and drying cycles, but their rate largely depends on the initial soil water content [Nachtergaele *et al.* 1998, Liu *et al.* 2005].

In a sloping vineyard, the soil water content can exhibit large positional variations due to weather conditions and shading by vine plants [Hicks 1973, Ham and Klutenberg 1993, Heilman *et al.* 1996, Verhoef *et al.* 1996]. The resulting large differences in water content may affect thermal conductivity and other soil thermal properties. The effect of water content on the soil thermal conductivity can be further enhanced by uneven distribution of bulk density or porosity as a result of greater loading beneath running gear in lower than upper portions of the slope owing to tilt of the tractor [Ferrero *et al.* 2005, Lagacherie *et al.* 2006]. It was observed under controlled soil water content and bulk density that at a given moisture content, increasing soil density increased thermal conductivity due to increasing contact area between soil particles [Sarwar and Majumdar 1995, Abu-Hamdeh and Reeder 2000, Abu-Hamdeh 2003, Lipiec and Hatano 2003].

The variations of thermal properties in a vineyard can also depend on whether the soil is cultivated or mulched. Under Swiss conditions, the effects of gravel mulch on the thermal and hydraulic characteristics of the soil (infiltration and evaporation) are perceived by the winegrowers to be most important advantages for wine growing [Nachtergaele *et al.* 1998]. The thermal and hydraulic properties affect diurnal temperature variation of the soil and near surface air as well as grape quality. Under dry Italian conditions, grass mulch improved grape quality but reduced its yield [Lisa *et al.* 1991]. Mulching also protects vineyards from frost [Nachtergaele *et al.* 1998, Lagacherie *et al.* 2006]. In general, soils with low thermal conductivities exhibit larger surface temperature changes at the same heat flux density [Abu-Hamdeh and Reeder 2000]. At the vine maturation period, cool nights increase the potential for colour and aromas of grapes whereas low soil water content, or lack of water, is favourable to the sensory wine quality [Riou *et al.* 1994, Huglin and Schneider 1998, Tonietto and Carbonneau 2004]. For this reason, the cool night index is used in the thermal characterization of regions [Nachtergaele *et al.* 1998].

On the scale of a vineyard, variability of the soil thermal properties is enhanced by variations in volumetric water content and bulk density in the inter-row induced by traffic associated with soil tillage, application of chemicals and grape harvesting. Therefore, the aim of this study was to determine the relations between the thermal properties and different water statuses (from dry to saturated) and positional variations and dispersion of the properties of the cultivated and grass-covered sloping vineyard soil within the inter-row.

MATERIALS AND METHODS

Soil and treatments

The experiment was conducted at Piedmont hillside viticulture (N-W Italy), 450 m elevation with average slope of 20% and south/south-west aspect. Annual rainfall in this region averages 840 mm and cold and snowy winter and dry summer with rainstorms characterise the climate. The vineyard is situated on Eutrochrepts of silt loam texture [Soil Taxonomy USDA 1975]. The management systems in the vineyard with rows following the contour lines included permanent grass cover (G) and cultivation treatment (C) applied in the vineyard for 10 years. The G treatment included three mowing and chopping operations of herbs left on the ground, one chemical weed control under the row, and fertilization by a subsoil distributor to drill the fertilizer to 0.15–0.2 m depth in the middle of the inter-row. The C treatment included autumn ploughing (0.18 m) and rotary hoeing in spring and summer to incorporate the herbs with the soil to 0.1 m depth. All tillage and chemical operations were done along the inter-rows across the slope with a crawler tractor (Fiat 55 CV) of 2.82 Mg weight and 1.31 m width at the same locations in both treatments. Total number of tractor passes per year was 14 and 11 under G and C, respectively. Ground contact pressures were 27.4 kPa and 38.0 kPa for upper and lower tracks, respectively. As a result, a greater surface deformation and rut depth under the lower than upper tracks along the slope was observed. This was more pronounced in cultivated than in grass covered soil.

The soil contained 30.5–33.3% sand, 55.8–59.2% silt, and 9.4–11.4% clay depending on the management system. The soil depth along the hillslope varied from 0.55 to 0.8 m. Organic matter content was 6.2 and 3.0% in permanent grass cover (G) and cultivation treatment (C), respectively. The soil was rather uniform in each of the two treatments and thereby we used the respective data for calculating the thermal properties characteristics.

The measurements were taken in early spring (5 March, 2001) and in autumn (16 October 2001) to reflect the characteristic conditions at the beginning and the end of the growing season of the vine trees. To determine soil water content and bulk density cores of 100 cm³ were taken on 30 m long four transects (10 m apart) transversal to the inter-rows (2.7 m width) at the depths of 0.01–0.08, 0.09–0.16 and 0.17–0.25 m in places corresponding to upper rut (UR), inter-rut (IR) and lower rut (LR) areas along the slope. That gave 36 data for each management system at every measurement date and soil wetness status. The areas are largely influenced by management practices and machinery traffic during growing season [Ferrero *et al.* 2005].

Mean daily topsoil temperature was about 15 and 20°C while sampling. In the laboratory, soil cores were first weighed and then water-saturated and then equilibrated in a pressure plate extractor at a water potential of 9.8 kPa (field

capacity) and dried in an oven (105°C, to constant weight). At each stage, weight of the cores was recorded. Then the data were used to compute water contents corresponding to four soil wetness statuses, that is dry, current, field water capacity and saturated and bulk density (ratio of soil dry weight to core volume) for each sampling event. The wide range of water status allowed reflecting large temporal variation of water content and thus thermal properties and heat flux.

Determination of thermal properties

Thermal conductivity of soil λ (W m⁻¹ K⁻¹) was estimated with the physical-statistical model described by the following equations [Usowicz 1992, Usowicz and Usowicz 2004]:

$$\lambda = \frac{4\pi}{u \sum_{j=1}^L \frac{P(x_{1j}, \dots, x_{kj})}{x_{1j} \lambda_1(T) r_1 + \dots + x_{kj} \lambda_k(T) r_k}} \quad (5)$$

where:

u – the number of parallel connections of soil particles treated as thermal resistors,

L – the number of all possible combinations of particle configuration,

x_1, x_2, \dots, x_k – number of individual particles of a soil with thermal conductivity $\lambda_1, \lambda_2, \dots, \lambda_k$ and particle radii r_1, r_2, \dots, r_k ,

$\sum_{i=1}^k x_{ij} = u, j = 1, 2, \dots, L, P(x_{ij})$ – probability of occurrence of a given soil particle

configuration calculated from the polynomial distribution:

$$P(x_{1j}, \dots, x_{kj}) = \frac{u!}{x_{1j}! \dots x_{kj}!} f_1^{x_{1j}} \dots f_k^{x_{kj}} \quad (6)$$

The condition $\sum_{j=1}^L P(X=x_j) = 1$ must also be fulfilled. The probability of selecting a given soil constituent (particle) $f_i, i = s, l, g$, in a single trial was determined based on fundamental physical soil properties. In this case f_s, f_l , and f_g are the content of individual minerals and organic matter – $f_s = 1 - \phi$, liquid – $f_l = \theta_v$ and air – $f_g = \phi - \theta_v$ in a unit of volume, ϕ – soil porosity.

The data on texture, organic matter content and solid phase densities of soil and organic matter were used to determine the probability of occurrence of given soil component. It was assumed that sand fraction consisted mainly of quartz; however, other minerals were contained in majority of silt and clay fractions. Based on the soil textural composition and solid phase density, content of quartz

and other minerals and organic matter per unit volume was calculated. The volumetric contents of quartz in the soil were 26.3 and 27.4% $\text{m}^3 \text{m}^{-3}$ under G, and 32.7 and 28.9% $\text{m}^3 \text{m}^{-3}$ under C at 0–0.15 and 0.15–0.3 m, respectively [Lipiec *et al.* 2007]. Corresponding contents of other minerals and organic matter were 59.1, 63.8, 60.6 and 66.1% $\text{m}^3 \text{m}^{-3}$ and 14.58, 8.81, 6.75 and 5.07% $\text{m}^3 \text{m}^{-3}$. The measured values of particle density were 2.43 and 2.54 Mg m^{-3} under G and 2.58 and 2.46 Mg m^{-3} under C at depths of 0–0.15 and 0.15–0.3 m, respectively.

We used this model since its good performance in predicting thermal conductivity had been shown for a wide range of soils at various water content, bulk density and temperature (T) (R^2 from 0.948 to 0.987; RMSE (root mean square error) from 0.083 to 0.132 $\text{W m}^{-1} \text{K}^{-1}$ and good agreement with measured data [Usovicz *et al.* 2006b]. The model data agreed also well with those of the standard model of de Vries [1963].

Volumetric heat capacity C_v ($\text{MJ m}^{-3} \text{K}^{-1}$) was calculated using empirical formulae proposed by de Vries [1963]:

$$C_v = (2.0f_m + 2.51f_o + 4.19\theta_v) \cdot 10^6 \quad (7)$$

where:

f_m, f_o, θ_v – volumetric contributions of mineral and organic components and water, respectively, $\text{m}^3 \text{m}^{-3}$.

Statistical analysis

To characterise the variability of the properties investigated we calculated mean, range, standard deviation and coefficient of variation. The calculation was performed for the whole inter-row including 3 positions, that is UR (upper rut), IR (inter-rut) and LR (lower rut) based on 36 data (depth 0–0.25 m) and for each inter-row position – based on 12 data. The means were calculated over all inter-row areas and depths for each soil water status. The differences between the management systems were analysed with reference to C and between the dates with reference to the spring date.

RESULTS AND DISCUSSION

The thermal properties were studied under two management systems with relatively uniform texture and soil organic matter content in each. Therefore, one separate set of soil water content and bulk density values with consideration of temperature for each management system to determine the soil thermal properties was used. Figures 1–4 present results of the statistical analysis for the respective variables covering all data for four soil wetness states in each management treatment. Moreover, results of statistical analysis of the variables with

depth along the sloping inter-row including rut and inter-rut areas for current soil water status were included (Figs. 5–6) with reference to their spatial distributions obtained from geo-statistical methods [Lipiec *et al.* 2007].

Bulk density

The bulk densities averaged across the inter-row areas were somewhat lower under G (1.197 Mg m^{-3}) than C (1.258 Mg m^{-3}) in spring, whereas in autumn they were almost the same in both treatments (1.232 Mg m^{-3}) [Lipiec *et al.* 2007]. The ranges of bulk density were 0.41 Mg m^{-3} under G on both measurement dates and under C it was 0.42 Mg m^{-3} in spring and 0.25 Mg m^{-3} in autumn. The dispersion, as indicated by standard deviation, under C was greater for the measurement data in spring than in autumn and the inverse was true under G. The differences between the measurement dates and management systems can be associated with different number and type of cultural practices under C and G [Ferrero *et al.* 2005] and with the loosening effect of frost during winter of winter conditions. Variability of bulk density, as indicated by coefficient of variation, was approximately 9% under G for both measurement dates and under C it was 9% in spring and 6% in autumn.

In spring, the lowest bulk density was in the surface soil (0.05 m) in all inter-row areas and the highest – in the central part (0.15 m) under the both ruts (Fig. 5a). However, in the inter-rut areas it increased with depth in both C and G. In autumn, the distributions of bulk density with depth in all inter-row areas under G and in inter-rut area under C were similar to those in spring, whereas under the ruts in C they were the greatest in the deepest soil (0.25 m) (Fig. 6a). In spring, under both management systems dispersion of bulk density was similar under both ruts and lower in the inter-rut area, likely due to the effect of freezing and thawing processes over winter and to the natural subsidence of soil. The effect of machinery traffic associated with management practices in the vineyard was more pronounced in the spatial distributions of bulk density at autumn than at spring, although patterns of the distributions were similar as shown earlier [Lipiec *et al.* 2007].

Water content

Four soil wetness statuses, from dry to saturated, were considered including the current status (Fig. 1). The current mean soil moisture contents (status 1), being $0.34 \text{ m}^3 \text{ m}^{-3}$ for C and $0.38 \text{ m}^3 \text{ m}^{-3}$ for G in spring, were close to those of field water capacity (pF 1.8–2.0) (status 2). In autumn, they were lower ($0.204 \text{ m}^3 \text{ m}^{-3}$ for C and $0.19 \text{ m}^3 \text{ m}^{-3}$ for G) and corresponded to soil water potential (pF 3.5–4.0). Greater soil water content under G than C in spring (by 10%) and lower in autumn (by 7%) can be a result of, respectively, greater water accumulation during winter and greater evapotranspiration during growing season. Saturated soil water content was similar in both management systems, with slightly

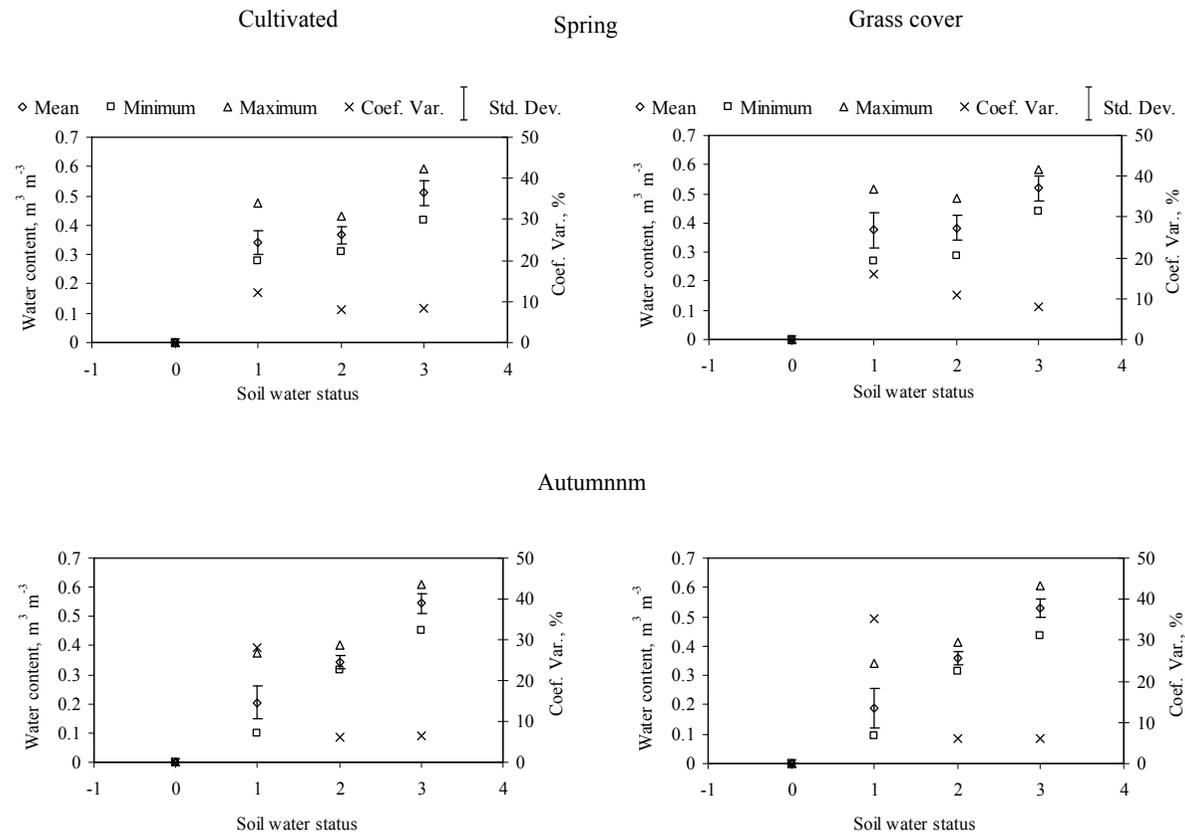


Fig. 1. Statistics of water content in topsoil (0–0.25 m) in cultivated (C) and grass covered (G) sloping vineyard for 4 soil wetness statuses: 0 – dry, 1 – current, 2 – field capacity, 3 – saturated; Coef. Var. – coefficient of variation, Std. Dev. – standard deviation, number of observation, $n = 36$

higher mean value in autumn ($0.608 \text{ m}^3 \text{ m}^{-3}$) than in spring ($0.584 \text{ m}^3 \text{ m}^{-3}$). The differentiation of water content was generally greater at the current state than at field water capacity and saturated statuses (pF 0) as shown by coefficient of variation and minimum and maximum values (Fig. 1). The values of coefficient of variation for current soil water content varied from 12 to 35% and for field water capacity and saturated states – from 6 to 11% depending on management system and date of measurement.

A greater differentiation of the current than adjusted soil water contents (Fig. 1) can be due to that the former being influenced by both different bulk density and soil water potential in various inter-row areas, whereas the latter reflects mostly bulk density variation. Decrease of total porosity and volume of large pores and increase of small pores volume with increasing bulk density lead in general to reduced water contents at saturation and high soil water potentials, and inversely at lower soil water potentials [Horton *et al.* 1994, Ferrero and Lipiec 2000].

In spring, soil water content with depth was changed only slightly at all inter-row areas under C (Fig. 5b). Under G, however, it decreased as depth increased in upper rut and inter-rut areas, whereas under lower rut it remained similar at all depths. In autumn, similarly as in spring, the differences in water content between the depths under both ruts were relatively small, whereas in inter-rut areas the water content was markedly greater at the central depth (Fig. 6b). At all comparable inter-row areas soil water content was greater in spring than in autumn. Lipiec *et al.* [2007] showed in the same experiment that spatial distribution of water content with depth and along the slope at spring under both C and G and at autumn under C was uniform. However, under G at autumn the distribution pattern was substantially different and showed trend of increasing water content along the slope.

In spring, dispersion of the soil water content values was greater under G than C at comparable inter-row areas (Fig. 5b). Irrespective of management system, the highest dispersion occurred under lower rut, whereas at the remaining two inter-row areas it was considerably smaller and similar. The differences were more pronounced under C than G. In autumn, however, the dispersion was highest in inter-rut area under both management systems (Fig. 6b). Under C the dispersion in upper rut was similar in spring and autumn, whereas in lower rut under C and both ruts under G it was lower in autumn. The above differences in water content are resultant of several factors, like evapotranspiration, bulk density, and shading by wine plants, the effect of which can be different depending on the inter-row areas and type of management system. Knowledge of the distribution of soil water content and other parameters along the slope and with depth can be useful in localized modification of thermal conditions to increase yield and improve quality of grapes.

Effect of soil wetness and bulk density on soil thermal properties

Thermal conductivity

As expected, thermal conductivity increased with increasing soil wetness but differed between the management systems at comparable wetness statuses (Fig. 2). Mean thermal conductivity values at spring measurement under C compared to G were greater by 1.5% (at field water capacity) to 5.1% (at dry state), whereas at autumn they were lower in C by 2.3% (at saturation) to 8.4% (at dry state). It is worthy to note that despite lower mean current soil water content under G than C (0.191 vs. $0.204 \text{ m}^3 \text{ m}^{-3}$), that typically increases the thermal conductivity, and at the same mean bulk density (1.23 Mg m^{-3}) in autumn, the thermal conductivity was somewhat greater under the former (0.792 vs. $0.765 \text{ W m}^{-1} \text{ K}^{-1}$). This apparent inconsistency can be due to greater variability of thermal conductivity in G than in C, as indicated by respective standard deviations of 0.234 and 0.199 , and coefficients of variation of 29.6 and 26.1% . The greater variability is generally associated with non-linear dependence of thermal conductivity on water content and bulk density [Usowicz *et al.* 1996]. In the range of low water contents (below field water capacity), small increase of water content at high bulk density can cause substantial increase in thermal conductivity, whereas at greater water contents (above field water capacity) the increases of thermal conductivity are smaller and depend more on bulk density than on water content. The foregoing implies that interpretation of thermal conductivity should include not only mean values but also dispersion.

The mean thermal conductivity at the current soil water contents in spring, being $1.165 \text{ W m}^{-1} \text{ K}^{-1}$ in G and $1.185 \text{ W m}^{-1} \text{ K}^{-1}$ in C, decreased in autumn by 32 and 35% , respectively. However, in the case of all the adjusted soil wetness states the differences were appreciably lower and varied from 2 (in G at saturated state) to 16% (in C at dry status). Values of standard deviation and ranges indicate that differentiation of thermal conductivity at both occasions was the greatest at current soil wetness state and the lowest at dry state. In both management treatments, standard deviation of thermal conductivity for current soil water content was somewhat greater in autumn than in spring. Consequently, coefficient of variation of thermal conductivity was greater for autumn than spring data (26.1 – 29.6 vs. 14.6 – 15.6%). The respective coefficient of variation values for all the adjusted wetness statuses were 5.5 – 17.8 and 7.6 – 22.4% (Fig. 2). This lower differentiation of thermal conductivity at the adjusted than current wetness statuses can be due to lower differentiation of water content at the same bulk density at comparable management systems and dates of measurement at the former.

The thermal conductivity was greater in spring than in autumn at all comparable inter-row areas and depths under C and G, which can be largely an effect of greater water contents (Figs. 5c and 6c) and associated water bridges between soil particles. In general, thermal conductivity on both measurement dates was

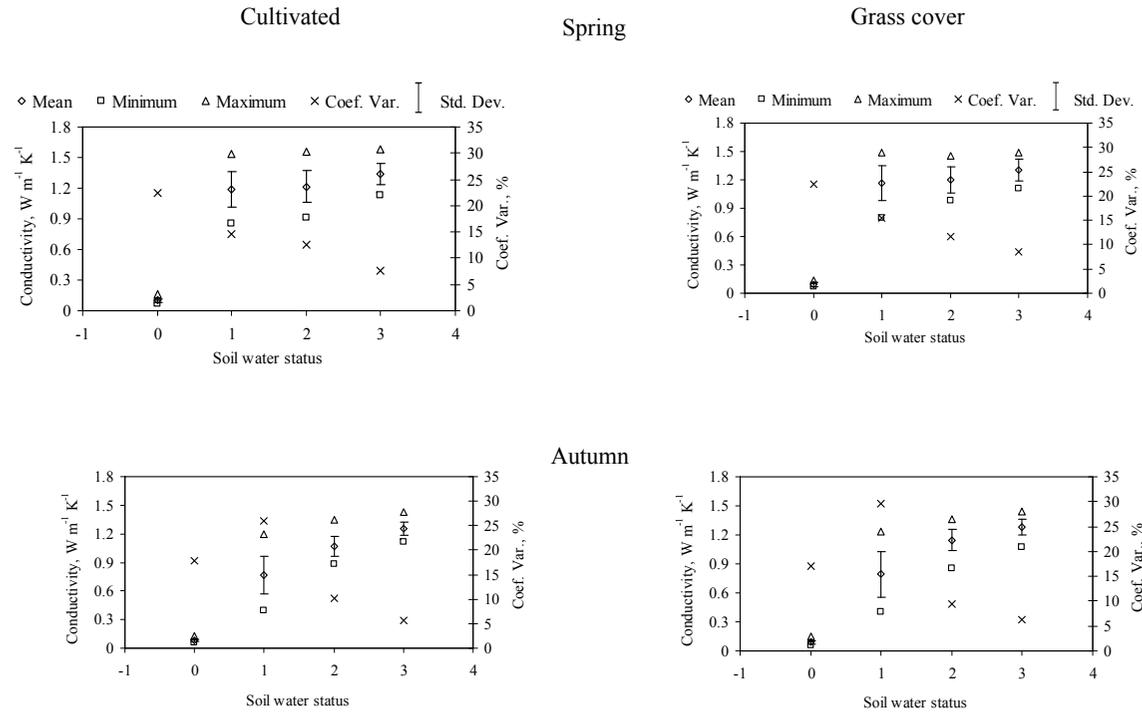


Fig. 2. Statistics of thermal conductivity in topsoil (0–0.25 m) in cultivated (C) and grass covered (G) sloping vineyard for 4 soil wetness statuses: 0 – dry, 1 – current, 2 – field capacity, 3 – saturated; Coef. Var. – coefficient of variation, Std. Dev. – standard deviation, number of observation, $n = 36$

greatest under lower ruts due to combined effect of greater soil water content and bulk density. Differentiation of thermal conductivity with depth in the inter-rut area was markedly greater in autumn than in spring, whereas under both ruts it was less visible. In addition, vine plants in the row can influence differentiation of the thermal conductivity and associated energy balance of a vineyard [Heilman *et al.* 1994, Verhoef *et al.* 1996]. Verhoef *et al.* [1996] showed that the thermal conductivity values were greater within-row than between-row soil, which was ascribed to lower soil evaporation in the former due to shading. The energy balance in a vineyard can be further modified by wind speed, aerodynamic conductance and surface temperature depending on inter-row position [Ham and Kluitenberg 1993, Heilman *et al.* 1996, Jacobs *et al.* 1996].

As can be seen from Figs. 5c and 6c, distribution pattern of thermal conductivity with depth in inter-rut area was more similar to that of water content than bulk density in autumn and inversely in spring. Lower dispersion (Std. Dev.) of the conductivity in spring than in autumn in the inter-rut area is consistent with the dispersion of water content but not with that of bulk density that was similar at both measurement dates. The dispersion in both ruts under G was lower in autumn than in spring, and the difference was more evident in lower than in upper rut. However, under C the dispersion in upper rut and lower rut was lower and greater in spring than in autumn, respectively. The opposite trends can be a result of cumulative and compensatory loosening effects of soil by winter freezing, tillage and different compaction level in upper and lower ruts.

Heat capacity

The heat capacity was more dependent on soil water content than on management system. Irrespective of management system and measurement date, the least heat capacity in dry state increased by more than three times at saturated state (0.933–1.006 vs. 3.173–3.212 MJ m⁻³ K⁻¹). The heat capacity in C compared to G was lower or higher depending on the soil water status and measurement date, but the differences were relatively small and varied from 0.3 to 4.9%.

The mean heat capacity at the current soil water content was notably greater in spring than in autumn for both management systems (by 26.5–31.4%), which is mostly a reflection of greater water content in the former and much less of bulk density that was similar on both measurement dates (Fig. 3). The differences between spring and autumn were notably lower at all the adjusted wetness states and varied from –2.4 to +7.3%.

Coefficients of variation of heat capacity were greater at current than at adjusted soil water statuses in both management systems and on both measurement dates. Slightly greater coefficients of variation values under G than C correspond with greater variability of soil water content under the former (Fig. 3). The coefficients of variation for the adjusted soil wetness statuses tended to be greater in spring than in autumn in both management systems.

Mean heat capacities, similarly as thermal conductivities, were greater in spring than in autumn at all comparable inter-row areas and depths under C and G, mostly due to greater water content in spring (Figs. 5d and 6d). Differentiation of heat capacity with depth and dispersion in the inter-rut area were greater in autumn than in spring, similarly as with thermal conductivity. Under the ruts, however, the differentiation with depth was somewhat different in spring and autumn, whereas dispersion was lower in autumn.

Thermal diffusivity

As can be seen from Fig. 4 the thermal diffusivity increased with increasing water content, reaching a plateau at and near field water capacity ($4.233\text{--}4.865 \cdot 10^{-7} \text{ m}^2 \text{ s}^{-1}$) and then declining up to saturated state irrespective of type of management and measurement date. However, rate of the increment was greater than that of the decline. Taking into consideration that this property influences movement of temperature wave, the above data implies that the fastest smoothing of field temperature will occur at approximately field water capacity and the slowest at dry wetness status.

Mean thermal diffusivities were slightly higher in C than in G at all comparable soil wetness statuses in spring, and the inverse was true in autumn (Fig. 4). The differences varied from 2.4 to 5.7% in spring and from -2.9 to -5.2% in autumn. Under G, the mean diffusivities were very similar in spring and autumn, whereas under C they were greater in spring than in autumn. Corresponding ranges of the differences were 0.2–3.2% and 5.8–13.0%, depending on soil wetness status. Verhoef *et al.* [1996] observed similar changes in vineyard soil thermal diffusivity at a narrow range of soil water content; however, artificial wetting resulted in a substantial increase of the diffusivity.

The dispersion of thermal diffusivity as shown by standard deviation values was greater at current than at adjusted soil wetness statuses. The standard deviations at current wetness state were $0.545 \cdot 10^{-7}$ and $0.388 \cdot 10^{-7} \text{ m}^2 \text{ s}^{-1}$ under G and C in spring and respectively increased in autumn by 38 and 78%, whereas at the adjusted soil wetness statuses they were greater in spring than in autumn under both management systems, by 16 to 34%. The lower dispersions of the diffusivity for the adjusted soil wetness statuses likely result from the same water potential in contrast to current water status where the potential may be different.

Comparison of Figures 5 and 6 indicates a greater differentiation of the means and dispersion of the thermal diffusivity than thermal conductivity and heat capacity. This results from the fact that the thermal diffusivity reaches its maximum at different water contents and bulk densities depending on their respective influence intensity on the diffusivity. Therefore, small changes in bulk density can substantially alter the diffusivity, whereas at the same bulk density and appreciable changes in soil water content the thermal diffusivity can remain almost unchangeable.

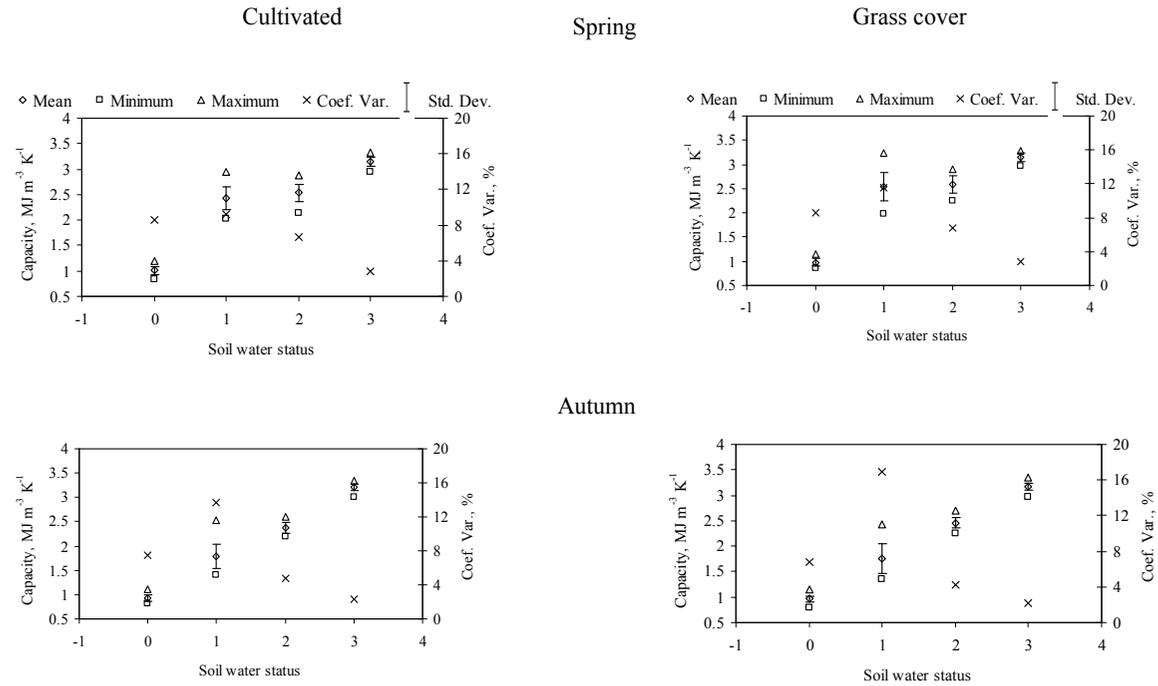


Fig. 3. Statistics of heat capacity in topsoil (0–0.25 m) in cultivated (C) and grass covered (G) sloping vineyard for 4 soil wetness statuses: 0 – dry, 1 – current, 2 – field capacity, 3 – saturated; (Coef. Var. – coefficient of variation, Std. Dev. – standard deviation, number of observation, $n = 36$)

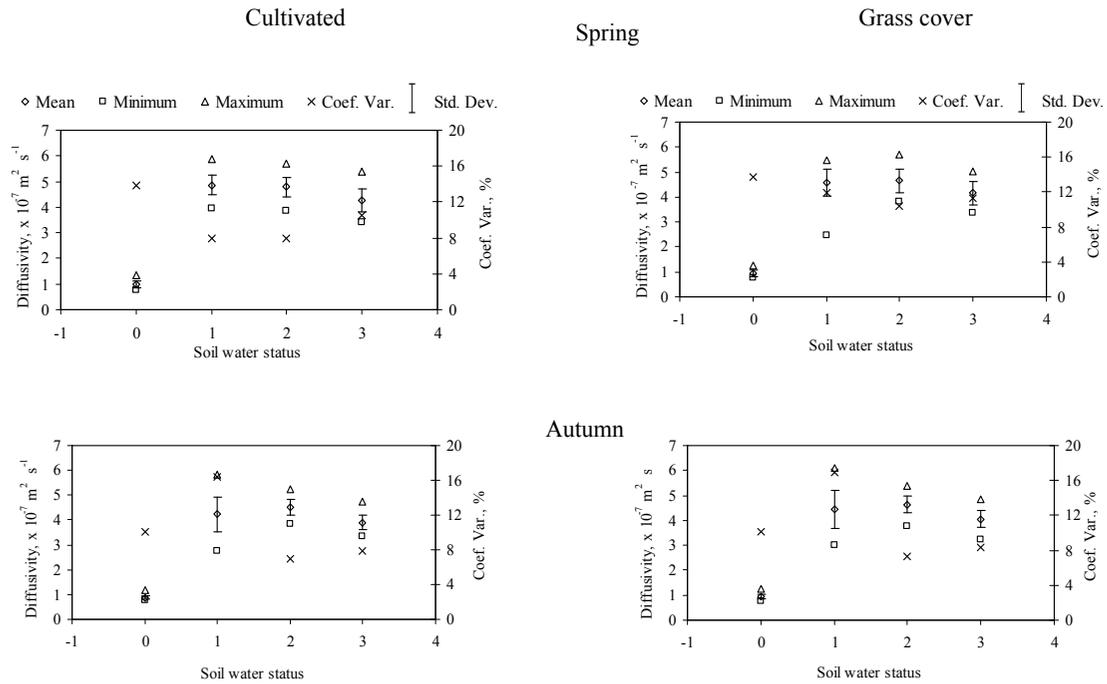
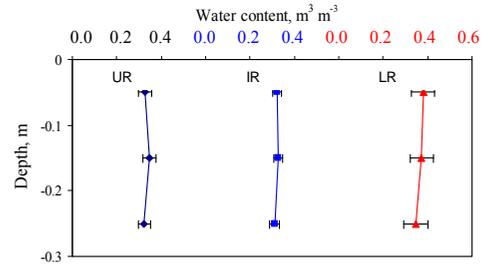
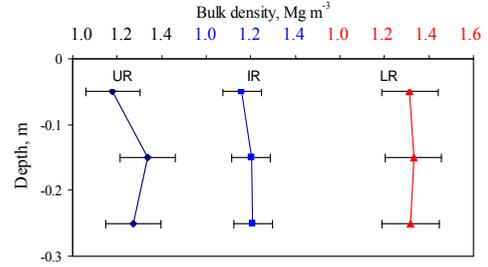


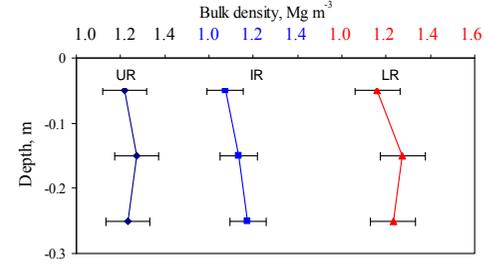
Fig. 4. Statistics of thermal diffusivity in topsoil (0–0.25 m) in cultivated (C) and grass covered (G) sloping vineyard for 4 soil wetness statuses: 0 – dry, 1 – current, 2 – field capacity, 3 – saturated; Coef. Var. – coefficient of variation, Std. Dev. – standard deviation, number of observation, $n = 36$

Cultivated

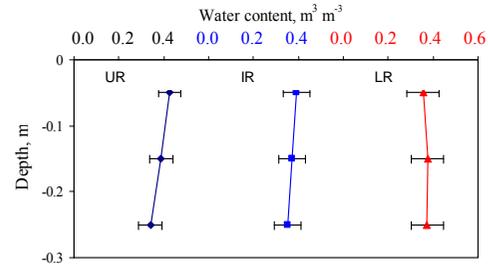


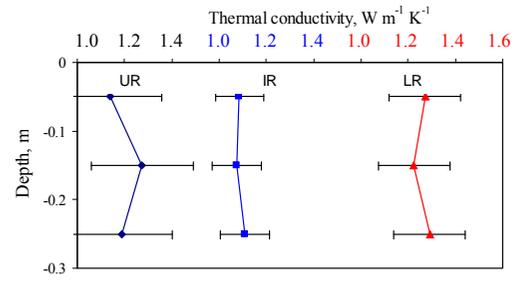
a)

Grass cover

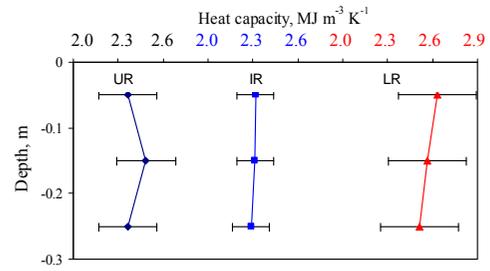
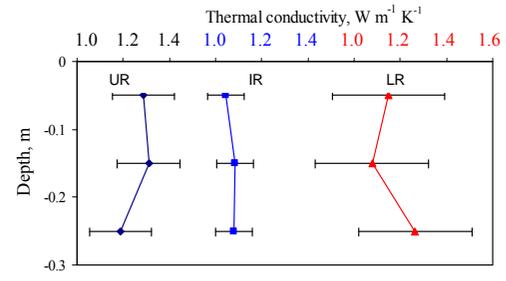


b)

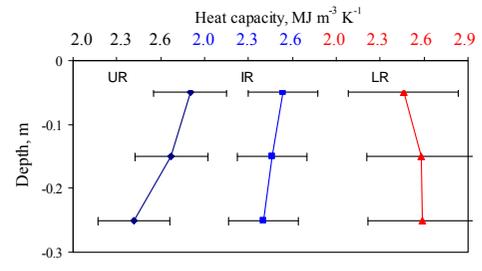




c)



d)



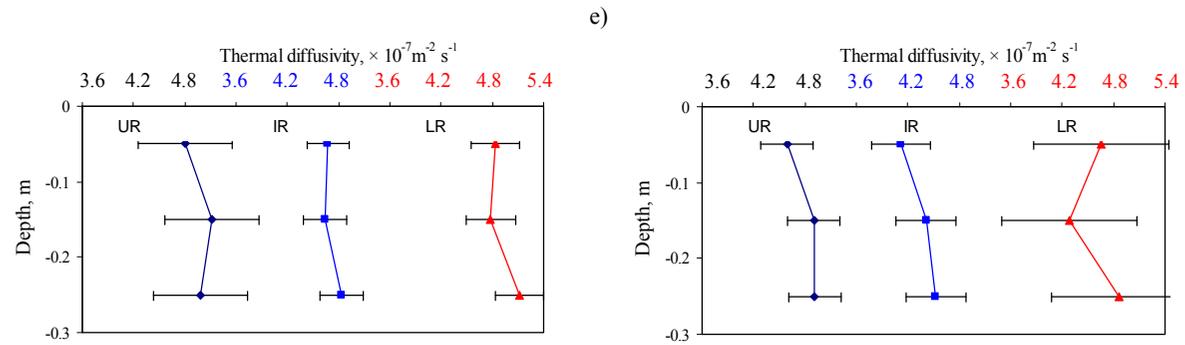
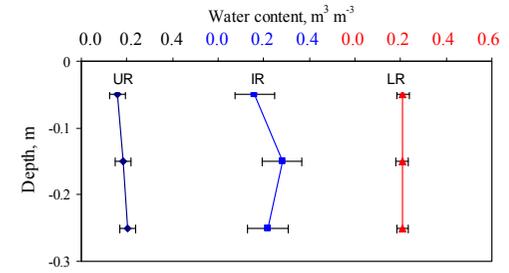
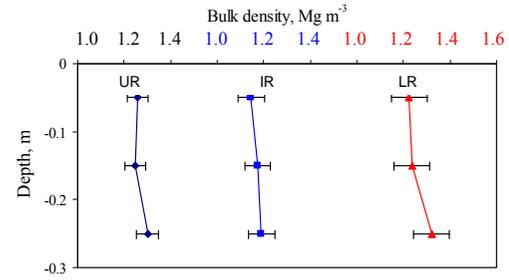


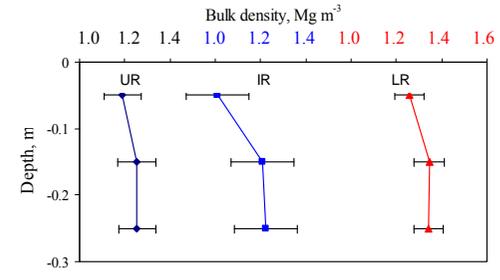
Fig. 5. Mean values and standard deviations of bulk density (a), water content (b), thermal conductivity (c), heat capacity (d), thermal diffusivity (e) for the cultivated and grass covered soil in spring; note that UR (upper rut), IR (inter-rut) and LR (lower rut), each inter-row area have a separate scale; means from 4 replicates at each depth and Std. Dev. from 12 data for layer of 0–0.25 m

Cultivated

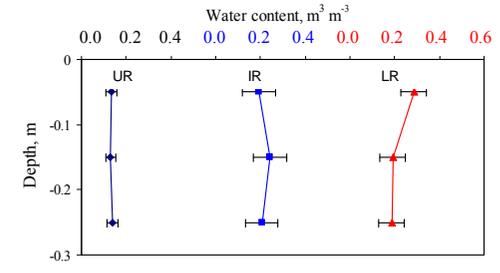


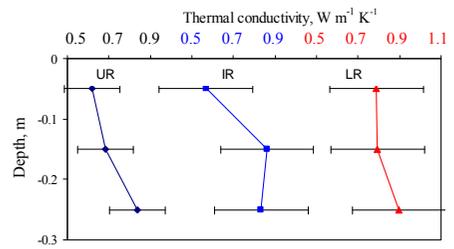
a)

Grass cover

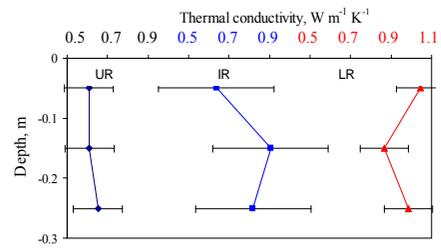


b)

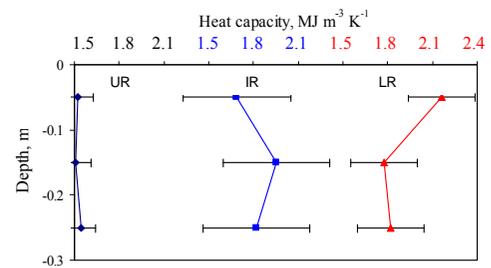
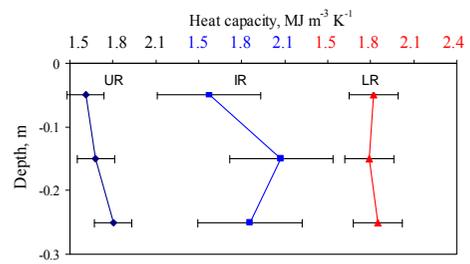




c)



d)



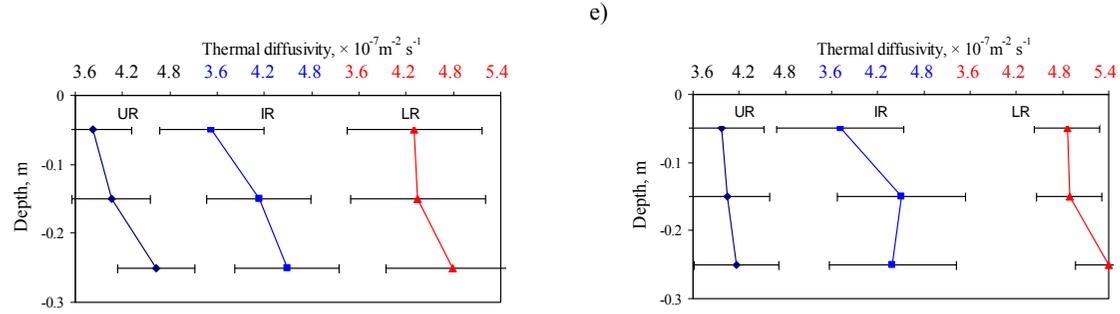


Fig. 6. Mean values and standard deviations of bulk density (a), water content (b), thermal conductivity (c), heat capacity (d), thermal diffusivity (e) for the cultivated and grass covered soil in autumn; note that UR (upper rut), IR (inter-rut) and LR (lower rut), each inter-row area have a separate scale; means from 4 replicates at each depth and Std. Dev. from 12 data for layer of 0–0.25 m

The thermal diffusivity, as with thermal conductivity and heat capacity, was greater in spring than in autumn at all comparable inter-row areas under C and G, which can be largely an effect of greater water content in spring (Figs. 5e and 6e). A greater evenness in the distribution of the thermal diffusivity with depth occurred in spring than in autumn. Absolute values of the diffusivity in surface layer were greater in spring than in autumn and similar in the deeper soil. Compared to spring, the differences in the diffusivity between the management systems were more evident in autumn when it was greater in G than in C. In an earlier study, under similar site conditions as this study, Lisa *et al.* [1991] observed that grass cover improved grape quality. Results of our study imply that one reason for this could be greater thermal diffusivity and associated faster smoothing of temperature field in G than in C at the end of growing season and faster heating of soil in spring. This was reflected in mean temperatures that were greater under G and C in spring and autumn, respectively [Lipiec *et al.* 2007].

Dispersion of thermal diffusivity (Std. Dev.) in the inter-rut area was substantially greater in autumn than in spring under both C and G (Figs. 5e and 6e). In the case of C, the dispersion at all comparable depths in upper rut was slightly lower in autumn than in spring, whereas in lower rut it was considerably greater in autumn. Such a course of changes of the thermal diffusivity can result from the fact that the diffusivities changed in the range of maximum values, where change of water content did not influence diffusivity. However, increase or decrease of the diffusivity was influenced by changes in bulk density (Fig. 4).

Comparison of Figures 5 and 6 indicate positional variation in dispersion of the thermal properties between the measurement dates. For instance, the dispersion of thermal conductivity in spring was largest under ruts whereas in autumn – in inter-rut area. Therefore, our results imply that differences in water content and bulk density in various inter-row areas should be considered in modelling approaches that generally assume spatial uniformity of the heat fluxes over a vineyard [Heilman *et al.* 1996, McInnes *et al.* 1996, Trambouze and Voltz 2001].

Differentiation of the thermal properties along the vineyard slope and shading by vine plants, influencing quantity of incoming radiation to the soil surface, has an effect on surface energy balance, including varying heat flux not only in the vertical but also in the horizontal plane. This leads to positional differentiation of soil temperature and microclimate along the slope. The temperature and microclimate can be modified during growing season by localized irrigation and cultural practices to accomplish the most favourable conditions for growth of vine and grape quality.

SUMMARY AND CONCLUSIONS

Effect of various states of soil wetness statuses (dry, current, field capacity, saturated) in rut and inter-rut areas within the inter-rows under cultivated and grass-covered sloping vineyard on thermal properties on two measurement dates (spring and autumn) was investigated. The results indicated seasonal and positional variation of the thermal properties in sloping vineyard that is influenced by management system. The whole range of water status allowed determining possible values of the soil thermal properties. The thermal properties can be modified by soil management practices and thereby have an effect on rate of soil heating and cooling.

In spring, the current wetness status was near field capacity and appreciably diminished in autumn. The thermal conductivity increased with increasing water content to a higher rate at the range of water contents from dry status to field water capacity than at higher water contents, whereas that of the heat capacity was uniform in the whole range of water contents. However, the thermal diffusivity had its maximum at or near field water capacity. The thermal diffusivity in spring and autumn at current wetness status was similar, despite considerably lower water content in the latter. This is a reflection of combined effect of soil water content and bulk density on the diffusivity, the maximum of which shifted towards lower water contents because of increased bulk density.

The dispersion of thermal conductivity and heat capacity was the highest at current soil wetness status and decreased successively at field water capacity, saturated and dry states. In spring, following the winter period without tillage, the dispersion of the soil thermal properties was lower in the inter-rut than under the rut areas. In general, tillage operations and traffic during growing season caused a decrease of the dispersion of the thermal properties in the ruts and at the same time an increase in the inter-rut area. These findings indicate that the variability of the thermal properties is dependent on the weather and associated soil water content, as well as on management practices during growing season, through their effect on soil structure and compactness. Therefore, this variability needs to be considered in modelling approaches of heat fluxes.

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CIEPLNE WŁAŚCIWOŚCI GLEBY NA ZBOCZU WINNICY W ZALEŻNOŚCI OD STANU UWILGOTNIENIA

Streszczenie. Znajomość właściwości cieplnych gleby pozwala oszacować przepływ ciepła jako jednej ze składowych bilansu cieplnego. Celem badań była ocena rozkładu przestrzennego właściwości cieplnych gleby (przewodnictwa cieplnego, pojemności cieplnej i dyfuzyjności cieplnej) w zależności od stanu uwilgotnienia i gęstości gleby uprawianej i z murawą. Próbkę gleby pobierano jesienią i wiosną w miejscach odpowiadających górnemu śladowi, między śladami i dolnemu śladowi ciągnika przejeżdżającego w poprzek zbocza. Oznaczono wilgotność aktualną (w czasie pobierania próbek) i przy potencjale odpowiadającym połowej pojemności wodnej (pF 2,0) oraz w stanie nasycenia gleby wodą (pF 0). W badaniach uwzględniono także glebę suchą. Dane wilgotności i gęstości, a także temperatury i uziarnienia zostały użyte do oszacowania właściwości cieplnych gleby. Przewodnictwo cieplne obliczono przy użyciu fizyczno-statystycznego modelu, pojemność cieplną – z formuły de Vriesa. Dyfuzyjność cieplną obliczono z ilorazu przewodnictwa i pojemności cieplnej. Aktualna zawartość wody w glebie była zbliżona do połowej pojemności wodnej wiosną i znacznie niższa jesienią. Przewodnictwo cieplne i pojemność cieplna rosły wraz ze wzrostem wilgotności gleby. Większy wzrost przewodnictwa cieplnego zaobserwowano w przedziale od stanu suchego do połowej pojemności wodnej niż przy dalszym wzroście wilgotności gleby. Natomiast wzrost pojemności cieplnej był jednostajny w cały zakresie uwilgotnienia gleby. Dyfuzyjność cieplna osiągnęła maksimum w stanie zbliżonym i odpowiadającym połowej pojemności wodnej. Jesienią dyfuzyjność cieplna przy aktualnej zawartości wody była nieco niższa niż przy połowej pojemności wodnej, mimo znacznie niższej aktualnej wilgotności gleby. Było to wypadkową oddziaływania wilgotności i gęstości na dyfuzyjność cieplną gleby. Zmiany dyfuzyjności cieplnej w zależności od stanu uwilgotnienia były podobne w glebie uprawianej i pod murawą. Rozrzut przewodnictwa cieplnego i pojemności cieplnej był największy przy aktualnej wilgotności gleby, a najmniejszy w glebie suchej. Na wiosnę rozrzut był mniejszy między śladami niż w obrębie śladów. Zarówno w glebie uprawianej, jak i pod murawą rozrzut właściwości cieplnych był mniejszy pod śladami wiosną niż w jesieni, podczas gdy między śladami – odwrotnie. Prawdopodobnie było to wynikiem uprawy roli i przejazdów ciągnika podczas sezonu wegetacyjnego. Wyniki wskazują na to, że w celu zwiększenia dokładności oceny bilansu cieplnego w winnicy należy uwzględnić zmienność przestrzenną właściwości cieplnych gleby między rzędami winorośli.

Słowa kluczowe: gleby, właściwości cieplne, stan uwilgotnienia, winnica, użytkowanie