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Impact of soil compaction and wetness on thermal properties of sloping vineyard soil

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Abstract

We assessed the effects of tilled (C) and grass covered (G) soil on the spatial distribution of the thermal properties in the vineyard interrow with consideration of areas corresponding to machinery traffic. To calculate the thermal conductivity (λ) we used a statistical-physical model, heat capacity (C_v) was calculated using formulae of de Vries and the thermal diffusivity (α) was obtained from the quotient of λ and C_v. The mean values of λ were generally greater under C than G in moist soil and the inverse was true in drier soil. The means of C_v were greater in moist and lower in drier under G than C and those of α were slightly higher in G than in C. In general the spatial distributions of both λ and C_v were similar to those of water content, however the distribution of α resembled well that of bulk density in both management systems.

Keywords: Thermal conductivity; Heat capacity; Thermal diffusivity; Soil compaction; Water content

1. Introduction

Soil thermal properties including thermal conductivity, heat capacity and thermal diffusivity are required in numerous agricultural, meteorological and industrial applications [9,33]. They play an important role in the surface-energy partitioning and resulting temperature distribution [12,21,28] and moisture flow and consequently form the soil and near ground atmosphere microclimate for plant growth [19,27] and the grape quality (e.g. [34]). Furthermore, the measurements of the thermal properties of soil analogues are useful in predicting these properties of extra-terrestrial porous media under space conditions [17,30,38].

The thermal properties are significantly influenced by variable soil water content, bulk density, temperature and by stable mineralogical composition and organic matter content [1,23]. The thermal properties as a function of water content are frequently reported in the literature (e.g. [3]) but more recent results [29,37] indicate that the changes in the thermal conductivity can be described by analytic functions with a greater accuracy when the air content rather than water content is used as independent variable. Change in soil bulk density and thus relative proportion of each phase will have an effect on the thermal properties and propagation of heat [22,31]. Increase of the thermal conductivity with increasing bulk density is ascribed to a greater contact between primary particles due to increase of volume fraction of solid phase [2,25]. The effect of soil bulk density on the thermal conductivity is more pronounced at high than at low soil water contents [35].

The temperature mediates the effect of soil water content on the thermal conductivity. The thermal conductivities of wet soil porous particles increased with increasing temperature in contrast to the behaviour of dry beds [6,8] and this increase was attributed to a greater thermal conductivity of water as well as to the temperature-dependent equivalent thermal conductivities arising from steam diffusion. In a

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Nomenclature

C	conventionally tilled
C_v	heat capacity ($\mathrm{M\,J\,m^{-3}\,K^{-1}}$)
f_l	content of liquid ($\mathrm{m^3\,m^{-3}}$)
f_g	content of air ($\mathrm{m^3\,m^{-3}}$)
f_s	content of solid phase ($\mathrm{m^3\,m^{-3}}$)
f_o	content of organic matter ($\mathrm{m^3\,m^{-3}}$)
G	permanently grass covered
L	number of all combinations of particles
P	polynomial distribution
$r_1, r_2, \ldots, r_k$	radii of particles (m)
R^2	determination coefficient
T	temperature (°C)
u	number of parallel connections of thermal resistors
$x_1, x_2, \ldots, x_k$	number of particles
x_s	content of minerals ($\mathrm{m^3\,m^{-3}}$)

Greek symbols

α	thermal diffusivity ($\mathrm{m^2\,s^{-1}}$)
θ_v	water content ($\mathrm{m^3\,m^{-3}}$)
ϕ	porosity ($\mathrm{m^3\,m^{-3}}$)
λ	thermal conductivity of soil ($\mathrm{W\,m^{-1}\,K^{-1}}$)
$\lambda_1, \lambda_2, \ldots, \lambda_k$	thermal conductivity of particles ($\mathrm{W\,m^{-1}\,K^{-1}}$)
λ_q	thermal conductivity of quartz ($\mathrm{W\,m^{-1}\,K^{-1}}$)
λ_m	thermal conductivity of other minerals ($\mathrm{W\,m^{-1}\,K^{-1}}$)
λ_o	thermal conductivity of organic matter ($\mathrm{W\,m^{-1}\,K^{-1}}$)
λ_l	thermal conductivity of water ($\mathrm{W\,m^{-1}\,K^{-1}}$)
λ_g	thermal conductivity of air ($\mathrm{W\,m^{-1}\,K^{-1}}$)
ρ	bulk density ($\mathrm{M\,g\,m^{-3}}$)

Subscripts

g	air
s	solid
l	water

study by Tarnawski and Leong [32] the soil thermal conductivity remained nearly constant within the water pressure head ranging from 1×10^3 to 1×10^5 m at low temperature (20 °C) while for higher temperatures (45 and 50 °C) from 5×10^3 to 1×10^5 m.

In sloping vineyards the soil properties influencing the thermal properties can be highly influenced by tillage operations before vineyard establishment [10] and then by management practices in the vineyard [37]. The mechanisation of all the cultivation practices of vineyard has increased the traffic intensity during the periods of the year when soil-bearing capacity is low. The repeated vehicular traffic, even if a light tractor is used, causes compaction of the traffic lanes, which can alter soil physical, hydrological properties and notably reduces water infiltration [15,25]. In different hilly areas of Central Italy [4] the controlled grass cover management in vineyards and orchards has proved to reduce tractor traffic and to mitigate soil erosion by reducing runoff but, in dry years, lowering of grape production.

When vine rows are across the slope, the machinery traffic associated with tillage, the application of chemicals and grape harvesting results in a greater bulk density of soil beneath the running gear to higher extent in the lower than upper portions of the slope [15]. The intensity of this compaction can be enhanced by typically higher soil water content in lower parts of the slope. The aspect of the vineyard and associated vine-row shadow can also influence variation in vineyard soil water content. The extent of the variation in bulk density, volumetric soil water content and associated air content influencing the thermal properties depends on whether the soil is cultivated or grass covered. However, very little research has been done to investigate the effects of the management systems on soil thermal properties in vineyards. Some research showed [41] that thermal conductivities were higher in within-row than between-row vineyard soil due to shadow cast by vine trees and thus reduced soil evaporation.

Therefore, our objective was to assess the effects of different water content, bulk density and air content on the thermal conductivity, heat capacity and thermal diffusivity of cultivated and grass covered soil in a sloping vineyard. We also assessed spatial distribution patterns of the properties as well as relationships between them in the vineyard inter-rows.

2. Materials and methods

2.1. Soil and treatments

The experiment was conducted at a site (450 m a.s.l.), with average slope of 18% and south/southwest aspect, representative of the hillside viticulture of Piedmont (NW Italy). The climate has cold winter with snow, dry summer with rainstorms: mean annual temperature 11.3 °C, mean of the monthly minima (January) −1.6 °C and of the maxima (July) 27.3 °C, long-term annual rainfall averages 840 mm. The vineyard, with rows following the contour lines, lies on silt loam soil resting on marls (middle Miocene) and is classified as Eutrochrepts. Some physical properties of the soil are given in Table 1. The experiment included management systems: (C) a conventionally tilled vineyard with autumn ploughing (18 cm) and rotary hoeing in spring and summer to incorporate the herbs with the soil to 10 cm depth, and (G) a permanently grass covered vine-

Table 1
Some physical properties of the cultivated and grass covered soil

	Tilled (*C*)		Grass covered (*G*)	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Texture (%, w/w)				
Coarse sand (2–0.2 mm)	6.85	5.85	5.66	4.88
Fine sand (0.2–0.02 mm)	27.89	26.10	25.48	25.01
Silt (0.02–0.002 mm)	55.84	57.54	57.50	59.22
Clay (<0.002 mm)	9.42	10.51	11.36	10.89
Particle density of soil ($M g m^{-3}$)	2.58	2.46	2.43	2.54
Organic matter ($g kg^{-1}$)	34.0	26.8	78.0	45.08
Particle density of quartz ($M g m^{-3}$)	2.65	2.65	2.65	2.65
Particle density of organic matter ($M g m^{-3}$)	1.3	1.3	1.3	1.3
Particle density of other minerals ($M g m^{-3}$)	2.68	2.47	2.61	2.66
Volumetric content of quartz ($\% m^3 m^{-3}$)	32.7	28.9	26.3	27.4
Volumetric content of other minerals ($\% m^3 m^{-3}$)	60.6	66.1	59.1	63.8
Volumetric content of organic matter ($\% m^3 m^{-3}$)	6.75	5.07	14.58	8.81

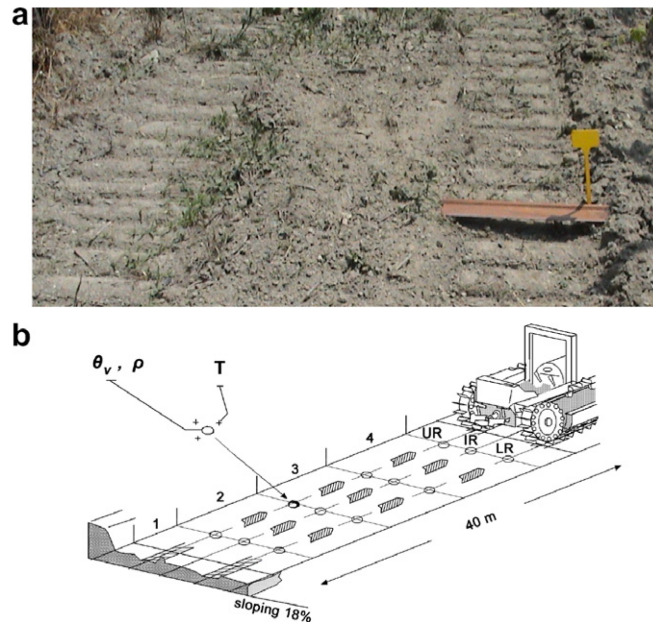

Fig. 1. Surface deformation caused by crawler tracks across the vineyard slope (a) and the schematic layout of measurement points in the inter-row. θ_v is the soil water content, ρ is the bulk density, T is the temperature (b); UR, IR and LR are the upper rut, inter-rut and lower rut areas, respectively; 1, 2, 3, 4 are the transects.

yard with 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 15–20 cm depth in the middle of the inter-row. In both management systems a crawler tractor of 2.82 M g weight and 1.31 m width was used for tillage and chemical operations along the inter-rows across the slope. These management systems were applied in the vineyard for 10 years.

2.2. Soil physical properties of the soil

The measurements of soil water content and bulk density were taken in early spring (5 March, 2001) and in autumn (16 October 2001) on four transects (10 m apart) transversal to the inter-rows (2.7 m width) (Fig. 1). The dates were selected so that to reflect the characteristic conditions at the beginning and the end of the growing season of the vine trees. In subsequent parts of the paper the respective dates will be called “spring” and “autumn”. Bulk density of soil was determined by the core method [5] at depths of 2.5–7.5, 10–15 and 17.5–22.5 cm using 100 cm^3 cores. The same cores were used to determine soil water content. Air content was obtained from the difference between volumetric water content at saturation, determined in laboratory and at current water content. The number of measurements in each management system and measurement date was thirty six covering soil profile and places corresponding to upper rut (UR), inter-rut (IR) and lower rut (LR) in the inter-row along the slope (four transects × three depths × three inter-row areas).

Soil temperature data were collected at 6 cm and 11 cm depths in three places corresponding to slope, middle slope and flat areas of each management system, by means of T-type thermocouples and computer datalogger. In each area the sensors were located in the centre and in the upper and lower ruts of the tractor in the inter-row (Fig. 1). Air temperature was recorded in the meteorological station situated within the area of the vineyard. Soil and air temperature readings were recorded hourly (one reading was the average of six measurements taken every 10 min) and presented in Table 2.

2.3. Thermal properties

The study employs the statistical-physical model of soil thermal conductivity proposed by Usowicz [35]. The model is expressed in terms of thermal resistance (Ohm’s law and Fourier’s law), two laws of Kirchhoff, and the polynomial distribution [13]. The volumetric unit of soil in the model consists of solid, water and air particles, and is treated as a system made up of regular geometric figures, spheres, filling the volumetric unit by layers.

The model assumes that connections between layers of the spheres and between neighbouring spheres in the layer are represented by serial and parallel connections of thermal resistors, respectively. A comparison of resultant resistance considering all possible configurations of spheres with a mean thermal resistance of a given unit soil volume, allows estimation of the thermal conductivity of soil λ (in $W m^{-1} K^{-1}$) according to the equation below [35]:

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

Table 2
Meteorological elements during measurements

Treatment	Date	Ambient		Soil				
		Weather	Air temp. (°C)	Condition	Grass cover (% of surface)	Temperature (°C)		
						Slope	Middle slope	Flat
Tilled	5/03/01	Clouds/sun	14.9	Wet surface	38	14.2	12.3	11.9
Grass covered					80	15.5	14.6	14.0
Tilled	16/10/01	Sun/clouds	20.3	Wet to dry surface	25	22.4	22.0	21.9
Grass covered					70	22.2	21.3	20.6

The soil temperature is a mean of measurements at 6 and 11 cm.

where u is the number of parallel connections of soil particles treated as thermal resistors, L is the number of all possible combinations of particle configuration, $x_1, x_2, \ldots, x_k$ are the numbers of individual particles of a soil with thermal conductivity $\lambda_1, \lambda_2, \ldots, \lambda_k$ for a given temperature T and particle radii $r_1, r_2, \ldots, r_k$, where $\sum_{i=1}^{k} x_{ij} = u$, $j = 1, 2, \ldots, L$, $P(x_{ij})$ is the probability of occurrence of a given soil particle configuration calculated from the polynomial distribution [13]:

$$P(x_{1j}, \ldots, x_{kj}) = \frac{u!}{x_{1j}! \ldots x_{kj}!} f_1^{x_{1j}} \cdots f_k^{x_{kj}}. \tag{2}$$

The condition $\sum_{j=1}^{L} P(X = x_j) = 1$ must be fulfilled. The probability of selection of a given particle f_i, $i = s, l, g$, in a single sample is determined based on soil properties. The values of f_s, f_l, and f_g are taken individually for composing fractions of minerals and organic matter as $f_s = 1 - \phi$, for liquids as $f_l = \theta_v$ and for air or gases as $f_g = \phi - \theta_v$ inside the unitary volume, and within the assumed porosity $-\phi$ ($m^3\ m^{-3}$).

The number of the required parallel and serial connections of thermal resistors in the model depends strongly on the water content and bulk density of soil. Increase in volume fraction of water and bulk density results in a greater number of water bridges between the solid particles and a greater number of contact points and thus contact area between the solid particles, respectively. The model was identified as a model that adjusts the number of parallel connections of thermal resistors (from 3 to 13) along with the change of the ratio of water content in the unit of soil volume to its porosity and changes the spheres' radii with the change of the organic matter content [35]:

$$r_k = 0.036 f_o + 0.044 \tag{3}$$

where f_o ($m^3\ m^{-3}$) is the content of organic matter in a unit of volume.

The stepwise transition of the value of "u" as a function of soil saturation with water causes a respective step increase of calculated values of the thermal conductivity of soil. To avoid such a transition, a procedure of intermediate determination of thermal conductivity in a range of soil water contents from dry to saturated state was proposed. According to the procedure the thermal conductivity is determined for two succeeding values: u and $u + 1$ and then the values corresponding to the water content $\theta_v(u)$, $\theta_v(u + 1)$. The linear equation given below determines thermal conductivity for the needed value of the water content of the soil θ_v:

$$\lambda = \lambda(u) + \frac{\theta_v - \theta_v(u)}{\theta_v(u+1) - \theta_v(u)} (\lambda(u+1) - \lambda(u)). \tag{4}$$

The input data needed for calculating the thermal conductivity using the computer software [39] based on Eqs. (1)–(4) comprise soil mineralogical composition, organic matter content, porosity, temperature, and water content. Moreover, the model requires reference data on the thermal conductivity of the following soil components: quartz (λ_q), other minerals (λ_m), organic matter (λ_o), water (λ_l) and air (λ_g). The measured soil temperature values (Table 2) were used to calculate the thermal conductivity of these components using the equations given in Table 3. Contents of main mineralogical components, mainly quartz and other minerals, can be obtained by direct measurements or by estimates based on textural composition. In the case of the estimate one should analyse carefully the origin of a particular soil and choose soil textural fraction, which represents most closely a given mineralogical component. It is accepted that quartz occurs mainly in the fraction 2–0.02 mm and other minerals in the fraction <0.02 mm (e.g. [11,29,38]). The data given in Tables 1–3 were used to calculate the thermal conductivity and heat capacity using a statistical-physical model [39] and an empirical formula [11], respectively.

In a wet porous medium heat flow can be increased by the equivalent thermal conductivity of vapour when water evaporates from the warm region of the pore and moves due to gaseous diffusion and condenses on the cold region

Table 3
Values and expressions for parameters used in calculating the λ of soils

Source[a]	Thermal conductivity parameters ($W\ m^{-1}\ K^{-1}$)	Expression, value[b]
	Quartz – λ_q	$9.103 - 0.028T$
2	Other minerals – λ_m	2.93
2	Organic matter – λ_o	0.251
1	Water or solution – λ_l	$0.552 + 2.34 \times 10^{-3}T - 1.1 \times 10^{-5}T^2$
1	Air – λ_g	$0.0237 + 0.000064T$

[a] 1. [24], 2. [11].
[b] T in °C.

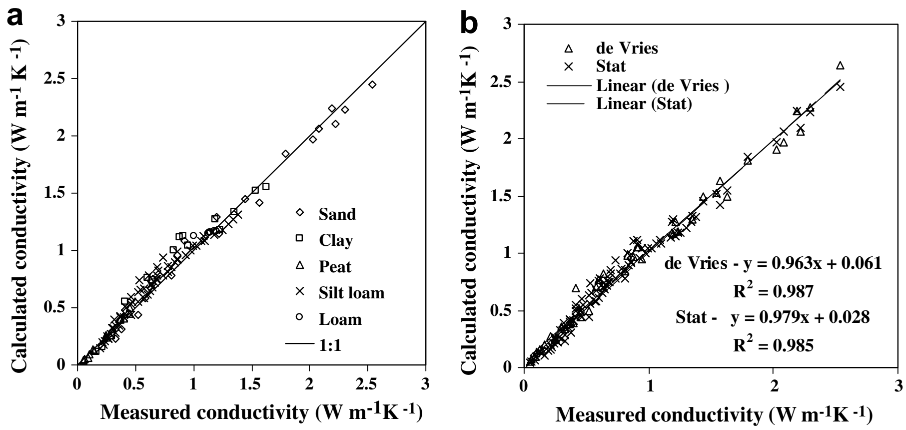

Fig. 2. Comparison of λ estimated by means of the statistical-physical model with measured for variously textured soils (a) and with those predicted by de Vries model (b). $\triangle$ refers to de Vries model and $\times$ (Stat) to the statistical-physical model. Solid line represents the relation 1:1 (a) and solid and dotted lines represent linear regression (b).

and results in flow of latent heat of vaporization ([6] and literature therein). This effect was included in the tested statistical-physical model by adding thermal conductivity of vapour to that of air.

A good agreement between the predicted λ by the statistical-physical model and the measured values ($R^2 = 0.985$) for a wide range of soil types at various water content, bulk density and temperature (T) is shown in Fig. 2a. Also, the values of the model predicted λ agreed well with those of the widely used De Vries model ($R^2 = 0.987$) (Fig. 2b) [11].

The volumetric heat capacity C_v (in J m^{-3} K^{-1}) was calculated using empirical formulae proposed by de Vries [11]:

$$C_v = (2.0x_s + 2.51f_o + 4.19\theta_v) \times 10^6 \quad (5)$$

where x_s, f_o, θ_v (m^3 m^{-3}) are volumetric contributions of mineral and organic components and water, respectively. The thermal diffusivity α (in m^2 s^{-1}) was calculated from the ratio of the λ and volumetric heat capacity C_v: $\alpha = \lambda / C_v$.

The statistical analysis was done using GeoEas [14] and GS+5 [16] software was used to visualise the results in 3D maps.

3. Results and discussion

The data in Table 1 indicate that grass covered soil has more sand and clay and less silt whereas cultivated soil has more sand and less silt and clay at the depth 0–15 cm than at 15–30 cm. In both management systems organic matter content was greater in the upper than in the deeper soil layer. The content of sand fraction was lower in G than C by 3.6% and 2.1% in the layers 0–15 cm and 15–30 cm, respectively. The content of silt was greater by 1.7% under G than under C in both layers. Also the clay content was slightly greater under G (by 1.9% and 0.4% at 0–15 and 15–30 cm, respectively). Organic matter content was greater under G than under C soil by more than twice and 1.7 times in 0–15 cm and 15–30 cm layers, respectively. A greater concentration of soil organic matter under grassed compared to tilled soil confirms the results of earlier studies (e.g. [18]). A greater content of fine particles under G than C can be a result of lower leaching and erosion.

The above-discussed data with consideration of particle density and bulk density were used to assess volumetric contents of minerals and soil organic matter. The volumetric contents of quartz and other minerals were somewhat greater and those of organic matter considerably lower under C than G at comparable depths (Table 1).

The bulk densities averaged across the inter-row areas were around 1.20 M g m^{-3} under both management systems for both measurement dates (Fig. 3). The ranges of the bulk density were 0.41 M g m^{-3} under G on both measurement dates and under C it was 0.42 M g m^{-3} in spring and 0.25 M g m^{-3} in autumn. A comparison of spring and autumn data indicate that the differentiation of bulk density under G, as shown by standard deviations, was somewhat greater in autumn than in spring and the inverse was true under C. Coefficient of variation (CV) was about 9% under G for both measurement dates and under C it was 9% in spring and 6% in autumn. These indicate consistent and declining differentiation between spring and autumn under G and C, respectively.

The mean volumetric soil water content in spring was 0.34 m^3 m^{-3} in C and greater by 10% in G (Fig. 3). Corresponding matric potential was close to that of field water capacity (pF 1.8–2.0). In autumn, however, the soil water content was lower in both management systems and it was greater by 7% for C than for G (0.19 m^3 m^{-3}). The values corresponded to matric potentials of pF 3.5–4.0 in both treatments. The air content, similarly to the water content, was surprisingly greater under C than under G on both measurement dates, which can be ascribed to slight reduction in bulk density under C and its increase in G soil from spring to autumn. The variability of volumetric water content and air content as indicated by the values of CV varied

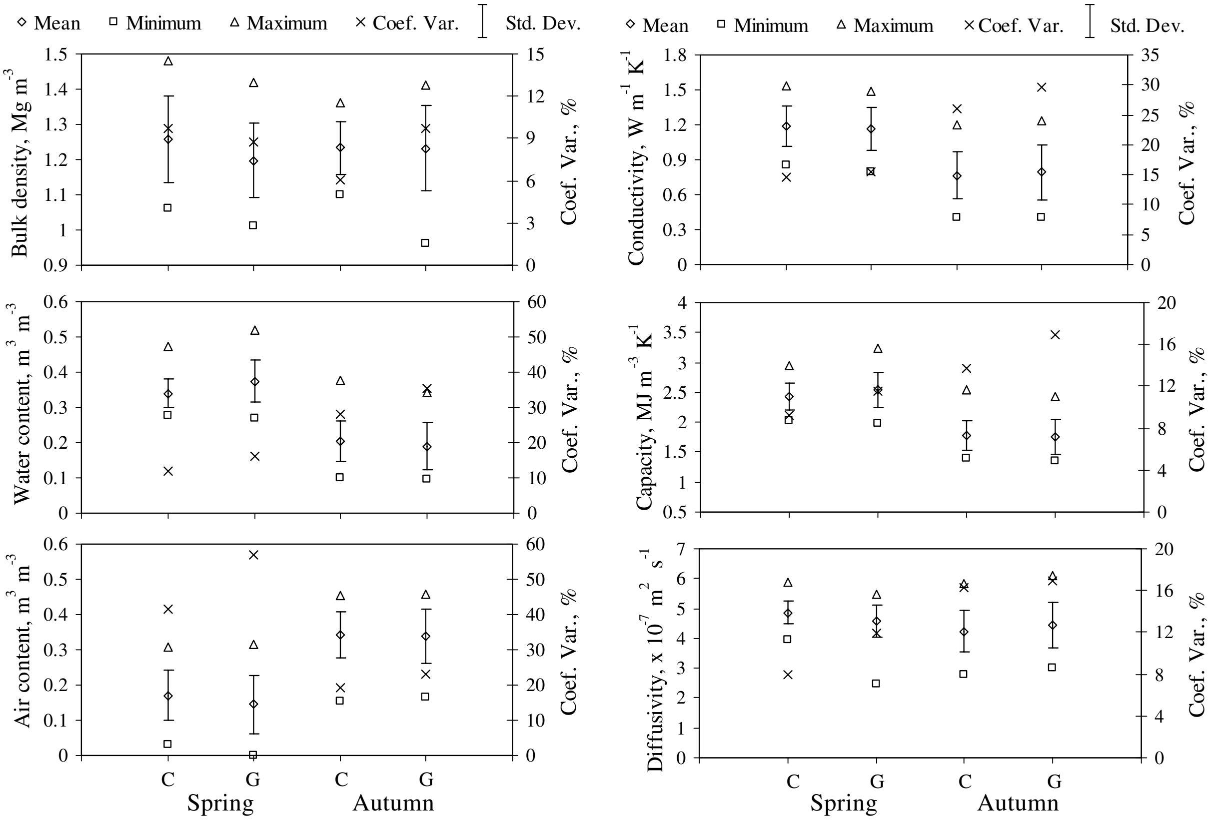

Fig. 3. Statistics of bulk density, water content, air content, thermal conductivity, heat capacity and thermal diffusivity of soil in 0–22.5 cm layer in the inter-row along the slope of the cultivated (*C*) and grass covered (*G*) vineyard in spring and autumn. Mean volume was calculated from 36 replicates.

from 12% to 35% and from 19% to 57%, respectively. On both measurement dates the CV values were lower in *C* than *G* by 20–36%.

Mean values of the λ under *C* were somewhat greater (1.7%) and lower (3.5%) than under *G* in spring and autumn, respectively. It is worth noting that in autumn, despite lower mean soil θ_v under *G* ($0.191\ m^3\ m^{-3}$) than under *C* ($0.204\ m^3\ m^{-3}$) and the same mean bulk density in both management treatments ($1.23\ M\ g\ m^{-3}$), the λ was somewhat greater in *G* ($0.792\ W\ m^{-1}\ K^{-1}$) than *C* ($0.765\ W\ m^{-1}\ K^{-1}$). This can be due to a greater variability of λ in *G* than *C* as indicated by respective standard deviations being $0.234\ W\ m^{-1}\ K^{-1}$ and $0.109\ W\ m^{-1}\ K^{-1}$ and CV 29.6% and 26.1%. The greater variability is associated with non-linear relation between λ and θ_v in which a small increase in water content in the range of low water contents (below field capacity) can result in a substantial increase in λ, to higher extent for greater than for lower bulk densities, whereas that in the range of greater water contents – the increases of λ are smaller and depend more on bulk density than on water content.

Irrespective of the management system the mean λ was $1.18\ W\ m^{-1}\ K^{-1}$ in spring and decreased in autumn by 32–35% (Fig. 3). The standard deviation in both management systems was slightly greater in autumn than in spring. However, the inverse was true with respect to the mean values. It was reflected in greater CV values in autumn (26.1–29.6%) than in spring (approximately 15%). The distribution of λ values can be largely associated with the changes in water content in various places of the interrow.

The mean heat capacities C_v in both management systems were similar in spring ($2.43–2.55\ M\ J\ m^{-3}\ K^{-1}$) (Fig. 3) and in autumn they were lower by 26.5–31%. The differentiation of heat capacity was related more to soil water content than to bulk density.

Irrespective of the type of management system and measurement date the thermal diffusivities ranged from 4.2×10^{-7} to $4.6 \times 10^{-7}\ m^2\ s^{-1}$ (Fig. 3). Mean thermal diffusivities were higher in *C* than in *G* in spring and the inverse was true in autumn with respective differences being 5.7% and 4.8%. Mean thermal diffusivities were only slightly different between spring and autumn under *G* (3.2%) whereas under *C* they were much greater in spring than in autumn (13.0%), which can be associated with non-linear response of the thermal diffusivity to bulk density and water content. The dispersion of the thermal diffusivity was greater under *G* than under *C* both in spring and autumn. The respective standard deviations were $0.545 \times 0^{-7}\ m^2\ s^{-1}$ and $0.388 \times 10^{-7}\ m^2\ s^{-1}$ in spring and were greater in autumn by 38% and 78%.

3.1. 3D MAPS

Fig. 4 presents 3D maps obtained by ordinary kriging of mean (over four transects and sampling position) bulk density, water content, air content, thermal conductivity, heat

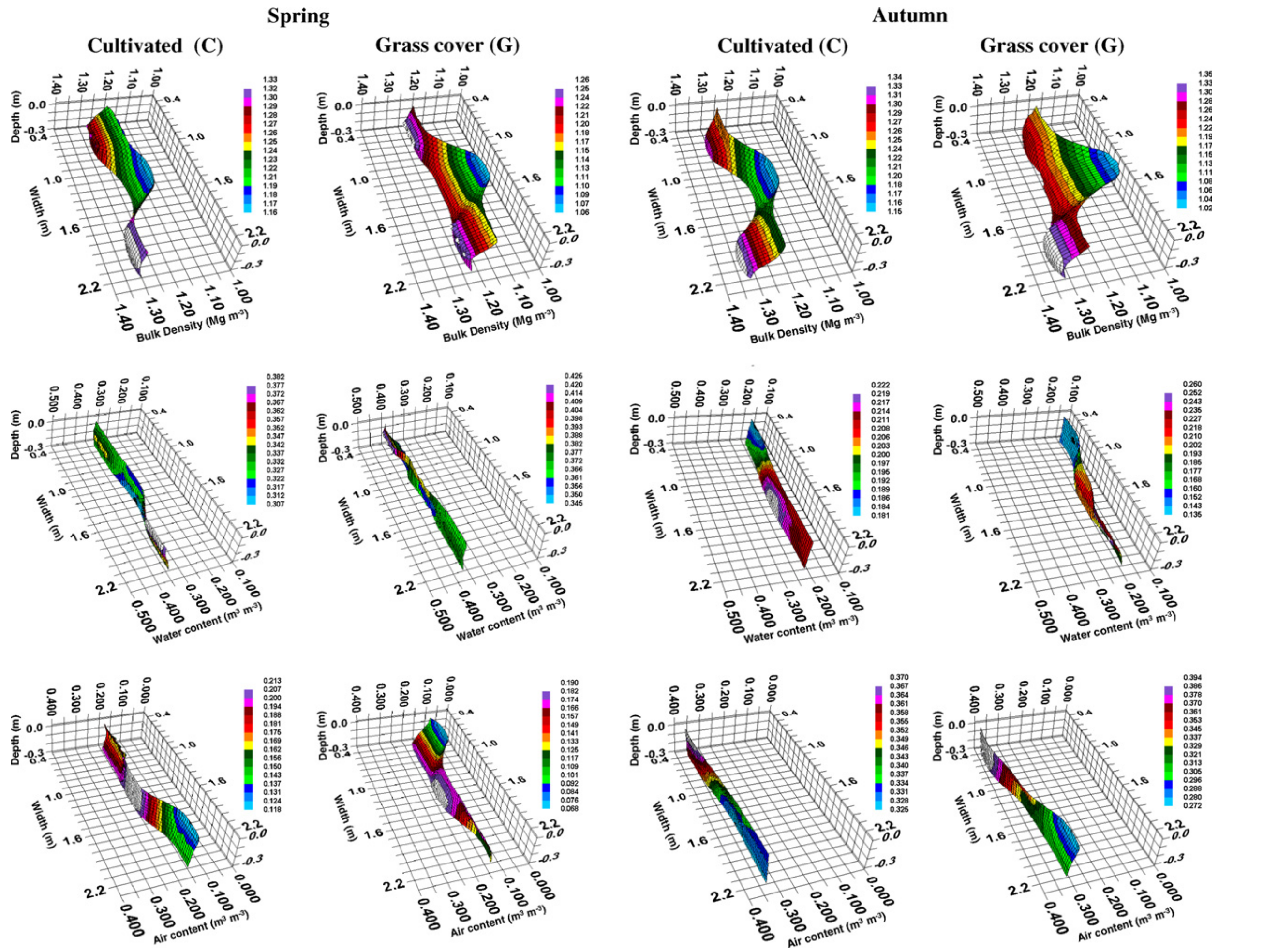

Fig. 4. 3D maps: bulk density, water content, air content, thermal conductivity, heat capacity and thermal diffusivity in the vineyard inter-row for the cultivated (*C*) and grassed (*G*) soil in spring and autumn.

capacity and thermal diffusivity of cultivated and grass covered vineyard. The spatial distributions of the characteristics were associated with places corresponding to the crawler rut and inter-rut areas (Fig. 1), part of the slope, type of management, depth and measurement date.

3.1.1. Bulk density

As expected, bulk densities were greater in places corresponding to the rut than to inter-rut areas (Fig. 4). The differences were more pronounced under *G* than under *C* in topsoil mainly due to smaller bulk density in the inter-rut area in *G*. The greatest bulk density under lower ruts can be in most cases a result of greater loading associated with the tractor's tilt and commonly higher water content along the slope enhancing soil compaction at traffic. As shown in an earlier study at the same site ground contact pressures were 27.4 kPa and 38.0 kPa for upper and lower tracks, respectively [15]. It is noteworthy that lower and upper crawler ruts are positioned in the upper and lower side of the same vine row in the sloping vineyard, which may result in uneven root growth and function. A greater bulk density under the ruts in autumn than in spring at comparable management systems in our study can be due to accumulation of compactive effect of tractor's traffic over the growing season.

The bulk density increased with depth irrespective of the management system and measurement date. This increase was more pronounced under *G* than under *C*, particularly in inter-rut area with the relatively low soil bulk densities and in the lower part of the slope with higher bulk densities. The lower densities under *G* than under *C* in the topsoil of the inter-rut area can be partly a result of greater soil organic matter in the former (Table 1). Vertical distribution of bulk density is one factor influencing soil quality.

3.1.2. Water content and air content

As can be seen from Fig. 4 the volumetric soil water content in spring was greater under *G* than under *C* at all comparable locations and depths. This can be associated with a greater water holding capacity due to higher soil organic matter of soil under *G*. However, in autumn, at the end of the growing season, the soil water content in most inter-row areas was lower under *G* than under *C*, which can be linked to a greater evapotranspiration of the grassed soil. In general the variations between the interrow areas

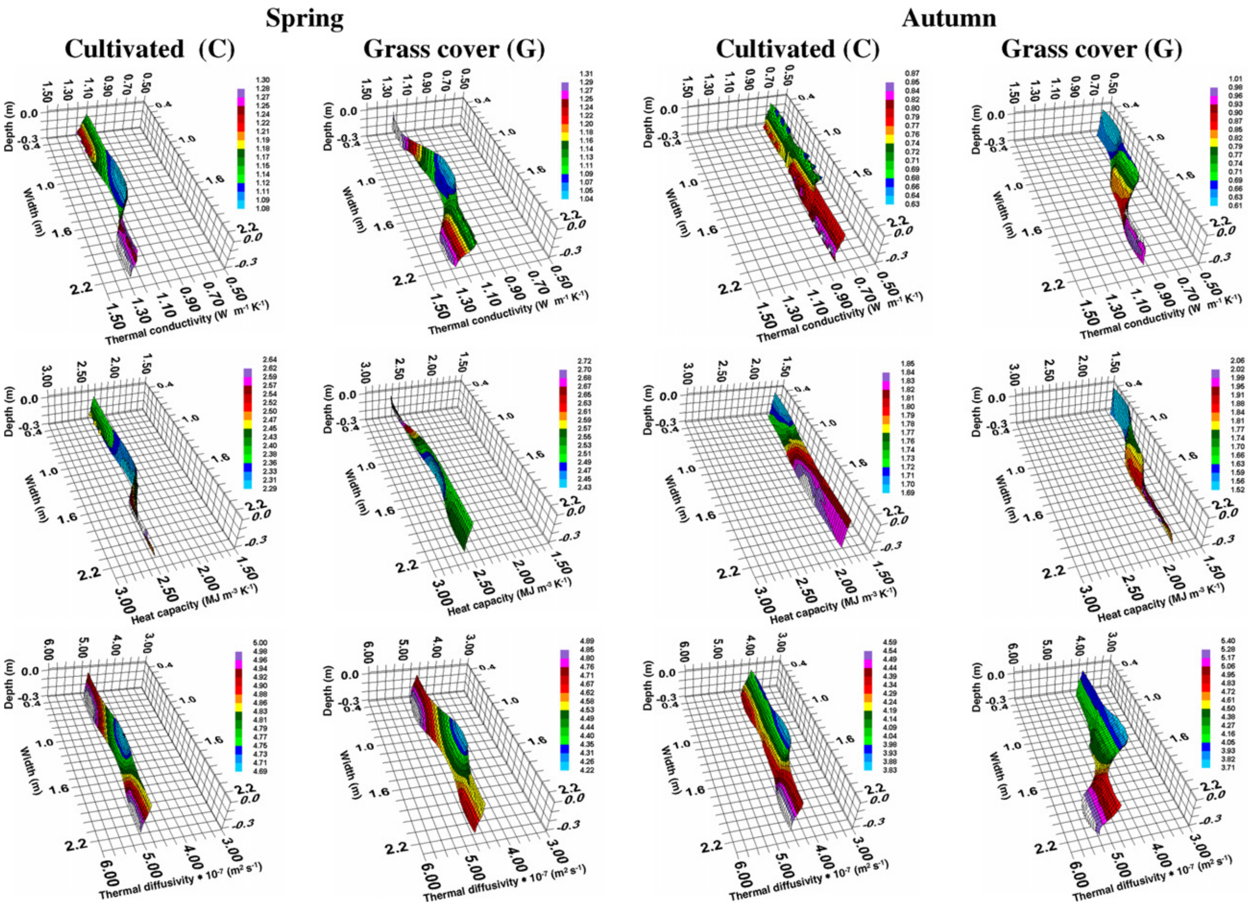

Fig. 4 (*continued*)

were smoother in spring than autumn under both management systems and in *C* than in *G* at both measurement dates. Fig. 4 also indicates that the soil water content in the upper rut was more uniform with depth than in inter-rut and lower rut areas down the slope.

As expected, air content decreased in areas with increasing water content and bulk density. In general, distribution pattern of air content resembled more that of water content than of bulk density.

3.1.3. Thermal conductivity

Distribution of the λ in autumn was similar to that of soil water content under both management systems. However, in spring, when the soil was wetter than in autumn, the distribution pattern of the λ was more similar to the mirror image of air content than to the actual pattern of water in both *C* and *G*. This similarity can be supported by the results of Ochsner et al. [29] indicating better relationship between air content and λ. The authors assigned this to the lower, by one order of magnitude, λ_g of air than the λ_l of water. Distribution of the soil λ in spring was also similar to that of bulk density and thereby volume of solid phase and number of contact points between the solid particles. The combined effect of bulk density and water content or air content on the λ is particularly visible in both *C* and *G* under the lower rut, and thus in the lower slope position, where the maximum λ corresponded to the largest bulk density and water content or the lowest air content resulting respectively from a greater tractor compactive effect and shading from vine rows reducing evaporation in this vineyard of south/southwest aspect. These data agree with results reported by Horn [20] and Usowicz et al. [36], indicating a greater increase in the λ with increasing bulk density at soil water content near field capacity than at lower soil water contents.

It is worth noting that the differences in the thermal conductivity between upper and lower rut areas in autumn were considerably greater in *G* than in *C* (Fig. 4). This is due to greater differences in θ_v between the areas in grassed *G* resulting from enhanced evapotranspiration of the less shaded upper rut area in the vineyard of south/southwest aspect. The results are consistent with earlier findings of Verhoef et al. [41] indicating a lower λ in wetter areas due to vine-row shadow.

Irrespective of the management system the values of the thermal conductivity were notably greater in spring than in autumn, whereas its range was greater in autumn (Figs. 3 and 4).

3.1.4. Heat capacity

The values of C_v were greater in spring than in autumn at all comparable interrow areas (Fig. 4). The differences between the interrow areas and with depth in each interrow area were relatively smaller than in the case of the λ. Distribution of C_v resembled mostly that of soil water content under both treatments and seasons and some similarity with bulk density could be observed in spring in both *C* and *G*.

3.1.5. Thermal diffusivity

The values of the thermal diffusivity, similarly to those of the λ and C_v, were greater in spring than in autumn for all comparable locations, with the exception of the lower rut area in *G* where they were greater in autumn (Fig. 4). The differences in the thermal diffusivity between the interrow areas in both management systems were more pronounced in autumn than spring. The changes with depth were more pronounced in inter-rut and lower rut areas under *G* than under *C* on both measurement dates. The distribution of the thermal diffusivity resembled mostly that of bulk density under both management systems, to a higher extent in autumn than in spring.

Overall, the above results indicate that the distribution patterns of the thermal properties are consistent with the positional distributions of rut and inter-rut areas, depending to different extent on management system and measurement date. The data taken under *G* in autumn (Fig. 4) clearly demonstrate that the lowest values of all the thermal properties occur in the upper ruts corresponding to the lower side of the vine row and the highest ones in the lower ruts corresponding to the upper side of the same row in the sloping vineyard. The positional variations of the thermal properties reflected the most distribution patterns of soil water content and bulk density. The differences in soil water content are largely due to uneven solar radiation due to shadow cast by vine trees and thereby different soil temperature and evapotranspiration along the slope. The variations under *C*, without grass cover, were less pronounced compared to *G* although the trend in soil water content was similar. Irrespective of management system, the differences in the thermal properties between the rut and inter-rut areas were less pronounced in spring than in autumn, which can be due to typically greater soil water content, owing to the winter rains and snow as well as to lesser differentiation in both water content and bulk density in the former. This comparison emphasizes the usefulness of geostatistical study for the identification of spatial and temporal effects as related to soil management practices, plant cover, slope position and weather conditions.

Since the differences in soil texture, organic matter content and temperature between the management systems (Table 1) as well as those in temperature between the measurement dates were not much different (Table 2), one can say that soil moisture content and bulk density were the main factors influencing the thermal properties under the management systems.

The areas with higher values of the thermal properties in the upper side of the vine row are accompanied by high soil bulk density (induced by tractor's tilt) (Fig. 4) and greater penetration resistance as indicated in our earlier study performed on the same site [15]. The positional variations of the thermal and mechanical properties may have important implications for vine growth conditions. For example, the areas with greater thermal conductivity and penetration resistance in the upper side compared with the lower side of the same row would show smaller soil surface temperature changes under the comparable heat flux densities and greater mechanical impedance for root growth. These plant growth factors can result in an uneven root growth and uptake functions of vine plants. These results accentuate the significant importance of precise management of fertilizers and other chemicals for getting better use of their efficiency and for avoiding leaching and/or accumulation.

The approach used and the interrelations obtained in this study indicate usefulness of combined measurements for determination of spatial and temporal variability of vineyard soil. Recent developments in simultaneous measurement of more than one property can be useful in further studies. Examples of this include a small multineedle probe for measuring soil thermal properties, water content and electrical conductivity [7,29], a device (MUPUS) for measurements of penetration resistance and thermal conductivity of terrestrial and extra-terrestrial porous media [26] or penetrometers equipped with TDR probe sensors for measurement of water content (e.g. [40,42]). The data on penetration resistance and water content or air-filled porosity can be satisfactorily used for predicting the soil thermal conductivity [37]. The use of such developments can be particularly useful in sloping vineyards for diminishing complications resulting from soil heterogeneity.

4. Conclusions

The results of soil thermal properties, water content, bulk density and air content in the sloping vineyard under *G* and *C* in spring and autumn were presented. Mean thermal conductivities and heat capacities were notably lower in drier autumn than wetter spring under both management systems and the mean thermal diffusivities were similar in both seasons under *G* and slightly greater in spring than in autumn under *C*. The mean thermal conductivities were somewhat greater under *C* than under *G* in spring and the inverse was true in autumn. The mean heat capacities were higher in spring than in autumn and similar under *G* and *C*. Mean values of the thermal diffusivity were similar in spring and autumn and tended to be higher in *C* than in *G* at spring and inversely in autumn.

By employing 3D geostatistical analysis it was possible to identify areas of different soil thermal properties in the vineyard inter-row. The data can be used for accurate determining of the spatial distribution of heat flux density. In general, the spatial variation of the thermal properties was more pronounced under *G* than under *C* in both seasons and in autumn more than in spring under both management systems. Soil water content, air content and bulk density were the main factors influencing the thermal properties. The results indicate that resemblance between the factors and the thermal properties was associated with the system of vineyard management, the measurement date and the kind of the thermal property. The spatial distributions of both λ and C_v were most similar to that of θ_v, however the distribution of α reflected well that of bulk density in both management systems. Knowledge on the spatial distribution can be useful in developing cultural practices for improvement of the soil thermal properties and quality and yield of grape.

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