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Evaluation of an indirect method for leaf area index determination in the vineyard: Combined effects of cultivar, year and training system

by

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Summary: The performance of the plant canopy analyzer LAI-2000 was evaluated in three seasons to estimate vineyard LAI (leaf area index) in the Bordeaux area. Measurements were made in a vertical-trellised vineyard with 5555 Sémillon and Sauvignon blanc vines per ha, and with 2525 lyre-trained Cabernet franc vines per ha. Various LAI-2000 sampling protocols were tested and the data compared with destructive determinations. While the results from single vines were not satisfactory, very good relationships were obtained if five consecutive vines were used. In the vertical-trellised vineyard, a very accurate and direct estimate of LAI could be obtained with the LAI-2000 using a combination of "parallel" and "diagonal" sampling protocol. LAI values obtained by direct and LAI-2000 had a 1:1 correspondence and were identical for both, year and cultivar. For the lyre system, a local calibration was required, mainly because of the contribution of shoots, perennial vine parts and posts. This calibration was easily obtained by progressively removing leaves from the vines.

Key words: gap fraction, leaf area index, training system, grapevine cultivar.

Introduction

The leaf area index (LAI) is an important biological parameter because it is a major determinant of evaporation and productivity of ecosystems. It is defined as the total one-sided leaf area per unit soil area. In viticultural studies, the LAI has rarely been measured. However, this parameter combined with canopy light microclimate evaluations could give a good estimation of the vine carbon balance and the qualitative potential of a vineyard (CARBONNEAU 1980; SMART 1985).

In general, direct leaf area measurements are laborious and expensive. Some methods are destructive or can not be applied to different treatments. Various indirect techniques utilise the relationship between canopy structure and radiation interception. Most of them measure the proportion of light which is not blocked by foliage in a range of azimuthal directions, i.e. the gap fraction. LAI is then estimated from the gap fraction data using different methods (WELLES 1990). The mathematical models used to evaluate the gap fraction assume that the foliage is randomly distributed which usually is not so. The degree to which an indirect method succeeds is determined in large part by how closely the real canopy conforms to the idealised model (WELLES and COHEN 1996).

The performances of several commercially available instruments based on the determination of the gap fraction have recently been reviewed by WELLES and COHEN (1996). In a row crop, such as many vineyards, a random distribution between rows can not be assumed, but distribution of the foliage within a row is more homogeneous. Consequently, sampling geometry becomes critical in row crops and indirect techniques have to be standardised to direct measurements. Two commercial instruments have been tested in vineyards: the DEMON (CSIRO, Canberra, Australia) by SOMMER and LANG (1994) and the LAI-2000 (LI-COR, Lincoln, Nebraska, USA) by SOMMER and LANG (1994), GRANTZ and WILLIAMS (1995) and WATANABE *et al.* (1997). The DEMON has given a reliable direct evaluation of LAI while at different locations the LAI was not as accurately estimated with the LAI-2000. In the best cases, a local calibration was required (SOMMER and LANG 1994; GRANTZ and WILLIAMS 1995). Different sampling protocols have been tested. e. g. WATANABE *et al.* (1997) showed that reading position, reading direction, view zenith angle and view opening angle have to be adapted to canopy structure. Generally these previous studies have been undertaken only in one year on vigorous vines planted at low density and with training systems allowing the shoots to grow more or less freely.

Our aim was to evaluate the LAI-2000 performance under different vineyard conditions. Our first goal was to find whether the LAI-2000 could be used in vineyards with high planting density, with a carefully trained foliage and with a trellis having a very regular or complicated geometrical shape. In case of a local calibration curve to be required, our second goal was to compare the effects of the season and the cultivar on the relationship between estimates made by LAI-2000 and direct measurements.

Material and methods

Field site: The leaf area index (LAI) measurements were conducted near Bordeaux in two different INRA experimental vineyards.

The first vineyard had a calcareous clay soil (Domaine de Couhins, Pessac-Leognan area) and was planted with 10-year-old Sémillon (clone 315) and Sauvignon blanc

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(clone 316) vines grafted to Fercal. The planting density was 5555 vines·ha^{-1} with a row by vine spacing of 1.8 m x 1 m and a north-south row orientation. The height of the trunk was 0.4 m and the vines were cane-pruned with two canes per vine. The shoots were vertical-positioned and the vines hedged at 1.4 m above the ground. This training system is referred to as "traditional" (Fig. 1 A). The second vineyard had a gravelly soil (Domaine du Grand Parc, Latresne, Premières Côtes de Bordeaux). Cabernet franc vines, grafted to 420 A, were planted in 1957 at an initial planting density of 5050 vines per ha. In 1987, every second row was removed and the vines were converted to a lyre training (Fig. 1 B, CARBONNEAU 1980) resulting in a plant density of 2525 vines per ha (3.6 m x 1.1 m). The row orientation was north-south. The height of the trunk was 0.5 m with two perpendicular arms of 0.3 m each to divide the canopy. Each side was pruned to an unilateral cordon 1m long. On both sides of the canopy, the shoots were positioned along an inclined trellis (15° from the vertical) with 4 wires, leading to two walls of vegetation trimmed outside, inside and at the top of the canopy at 2 m above the ground.

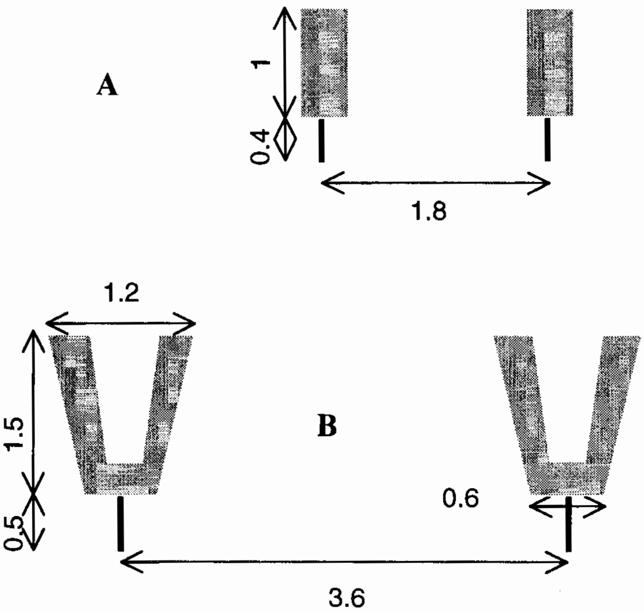

Fig. 1: Schematic view of the training systems: **A**, "traditional", **B**, lyre. Distances in meters.

L A I m e a s u r e m e n t s : Indirect measurements were made using the LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln, NE, USA). This instrument is equipped with hemispherical optics and a ringed detector that simultaneously measures diffuse radiation in 5 distinct angular bands about the zenith. A reference reading is made above the canopy, followed by below canopy readings. Gap fractions are computed at the 5 angles of view. The light sensor includes a filter to exclude radiation above 490 nm (WELLES *et al.* 1996). More details are available from SOMMER and LANG (1994), STENBERG *et al.* (1994), HICKS and LASCANO (1995) and LI-COR Corporation (1989).

We measured under very clear sky conditions during the last hour before sunset. A cap covering 87.5 % of the optic was used to limit the azimuthal field of view. Each reference reading well above the canopy was followed by 10 readings below the canopy, on the ground and in a straight line at 0.2 m intervals. This procedure was repeated at the 5 adjacent vines. Sampling protocols were chosen according to preliminary experiments. For the first protocol named "parallel" (Fig. 2 A), measurements were made along the row at a fixed distance from the vines (0.9 m for the "traditional" system, 1.4 m for the lyre system). The view was facing west in the direction of the vines. For the "traditional" training system, a second protocol was used named "diagonal" (Fig. 2 B). In this case, measurements were made from north-west to south-east, along a diagonal transect going from below the vine row to the middle of the row. The view was facing down the row towards south-west. The second protocol was not used for the lyre system because preliminary tests produced very poor results. At each date, the measurements were conducted on duplicate sets of 5 vines.

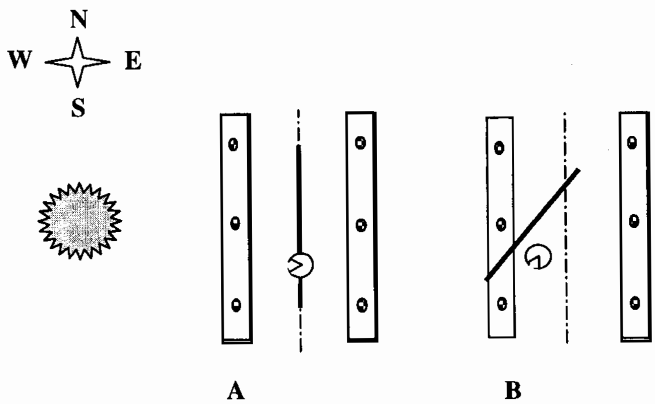

Fig. 2: Schematic protocols to collect the LAI-2000 data: **A**, "parallel", **B**, "diagonal". In each case 10 below canopy readings were performed on the ground at 0.2 m intervals along a two meter distance. This sequence was repeated in front of 5 adjacent vines. For the "parallel" protocol, the ruler was positioned at 0.9 m from the measured vine (mid-row) for the "traditional" system, and 1.4 m from the measured vine for the lyre system. The "diagonal" protocol was only used for the "traditional" system, the ruler going from below the row to the mid-row. A 315° covering cap was always used. The measurements were made facing west during the last hour before sunset.

For comparison, direct leaf area measurements were performed destructively the day after the LAI-2000 determinations. Leaves were removed from each vine, oven-dried for 48 h at 100 °C and weighed. Leaf area was calculated by using a regression equation between the leaf area and the dry weight of a sub-sample of leaves. Separate regressions were established each year for each cultivar.

E x p e r i m e n t s : Measurements of the leaf area index were conducted in 1994 and 1995 for both training systems on June 15, July 15, August 15 and September 15. For the "traditional" system, the measurements were carried out in 1994 on the cultivar Sauvignon blanc and in 1995 on the cultivar Sémillon.

In 1997, some additional measurements were obtained from lyre-trained vines during the second half of July. For these measurements the leaves were removed progressively, approximately a quarter of the total leaf area each day. Each fraction was dried and weighed separately. LAI-2000 measurements were performed the day before the first leaf removal and then, after each leaf removal. A final measurement was done after all leaves had been removed to evaluate the contribution of the shoots, the perennial parts and the posts to the LAI-2000 readings.

Results

P r o t o c o l e v a l u a t i o n o f t h e "t r a d i t i o n a l" t r a i n i n g s y s t e m : Fig. 3 shows the relationship between the LAI–2000 estimation and the direct LAI measurement for each vine in 1994. Parts A, B and C show the relationships for the "parallel" protocol, the "diagonal" protocol and their arithmetical average respectively. The correlation coefficients of the linear regressions were low but significant at the 1 % level. The best estimation was produced from the average values. Regardless of protocol, LAI of small vines were underestimated and that of large vines overestimated.

LAI estimations were greatly improved when the data were averaged for each group of 5 vines (Fig. 4). The correlation coefficients were significant at the 1 % level. With the "parallel" protocol (Fig. 4 A), the correlation was high but the LAI–2000 readings overestimated the LAI ($y = 0.76x + 0.23$, $r^2 = 0.91$, $n = 8$). The "diagonal" protocol (Fig. 4 B) gave the worse results according to the r^2 value ($y = 1.37x - 0.65$, $r^2 = 0.74$, $n = 8$). The average between both protocols (Fig. 4 C) again, gave the best estimate of LAI ($y = 1.12x - 0.43$, $r^2 = 0.97$, $n = 8$). Concerning the average between both protocols, the linear regression was forced through zero ($y = 0.95x$, $r^2 = 0.95$, $n = 8$). The coefficient of correlation was still very high and the slope was close to 1. Linear regression equations without intercept were calculated for two different sub-sample sizes. Regardless of whether the data were averaged for 4 or 5 adjacent vines, the coefficient of correlation was higher than 0.9 and significant at the 1 % level (Table).

T h e "t r a d i t i o n a l" t r a i n i n g s y s t e m; e f f e c t o f y e a r a n d c u l t i v a r : The same protocols were used in 1995 for the Sémillon vines with an identical training system. When the results of 5 vines were averaged, the linear regressions were very similar to those obtained in 1994 (Fig. 5).

T a b l e

Slopes and correlation coefficients for the linear regressions forced through zero between LAI-2000 determinations (average between the "diagonal" and the "parallel" protocols) and the direct LAI measurements made destructively, for different sub-sample sizes. Each sub-sample was extracted from the 5-vine sample

	Slope	Correlation coefficient
3 vines : sub-sample 1	0.94	0.92
3 vines : sub-sample 2	0.96	0.96
3 vines : sub-sample 3	0.92	0.86
4 vines : sub-sample 1	0.94	0.98
4 vines : sub-sample 2	0.86	0.95
5 vines	0.95	0.97

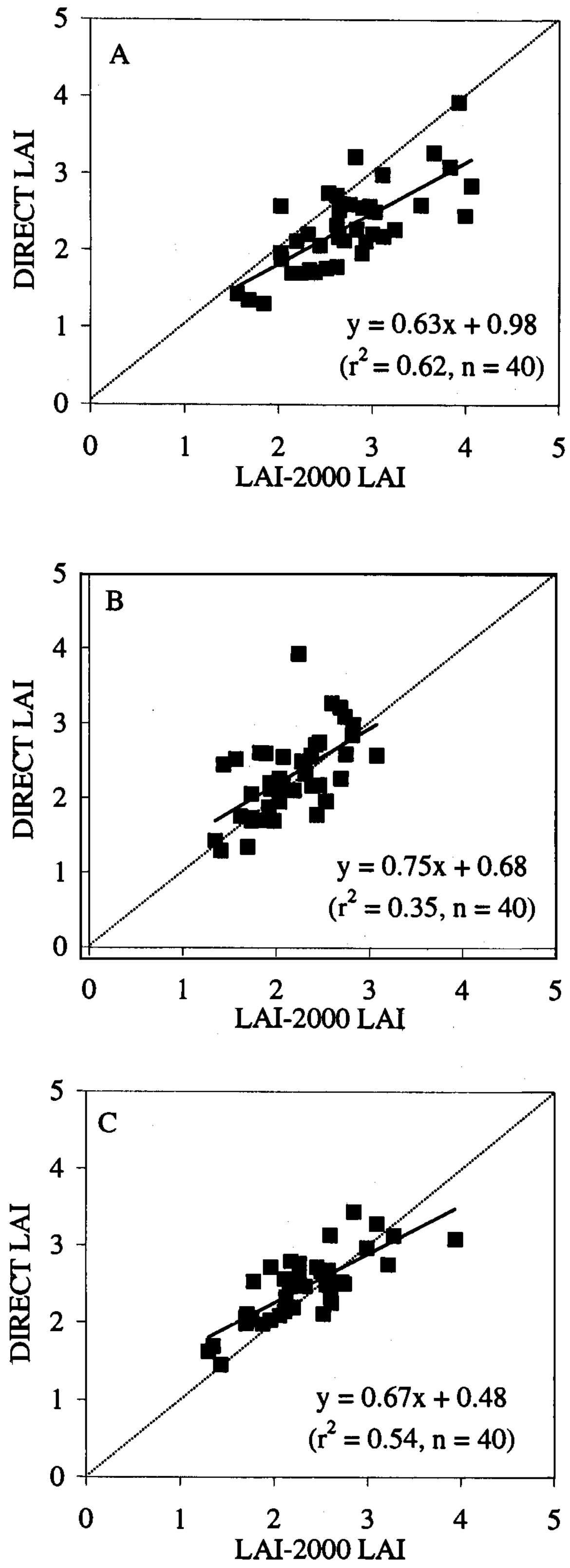

Fig. 3: Relationships between LAI-2000 data and direct LAI determinations made destructively, for each vine, obtained in 1994 in the "traditional" system, with the "parallel" protocol (**A**), the "diagonal" protocol (**B**) and the arithmetical average of both (**C**). Full lines represent the linear regressions and dotted lines the 1:1 relationship.

In 1995, the "parallel" protocol gave the highest correlation coefficient (Fig. 5 A, $y = 0.63x + 0.48$, $r^2 = 0.91$, $n = 8$). The LAI-2000 still overestimated the LAI. A comparison of the linear regressions of 1994 and 1995 did not indicate a signifi-

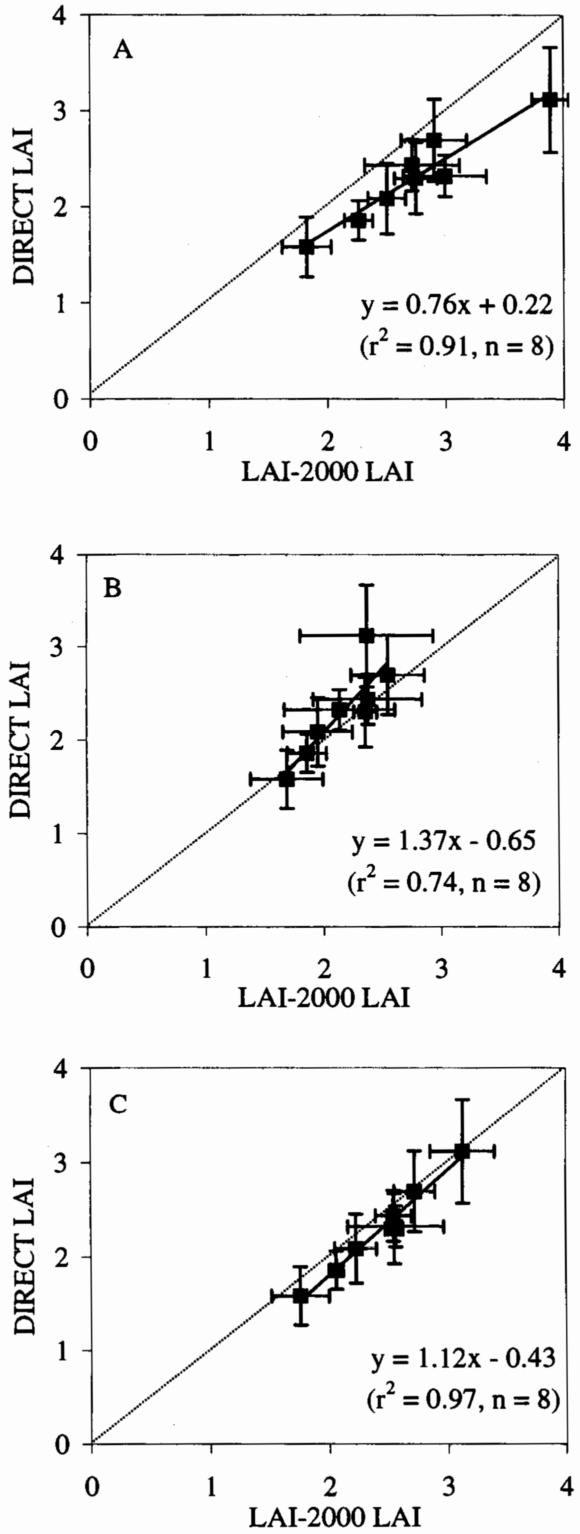

Fig. 4: Relationships between the average LAI-2000 data and the average direct LAI determinations made destructively, for a group of 5 vines, obtained in 1994 in the "traditional" system, with the "parallel" protocol (**A**), the "diagonal" protocol (**B**) and the arithmetical average of both (**C**). Full lines represent linear regressions and the dotted lines the 1:1 relationship. Horizontal and vertical bars represent the standard deviation of LAI-2000 and direct determinations respectively.

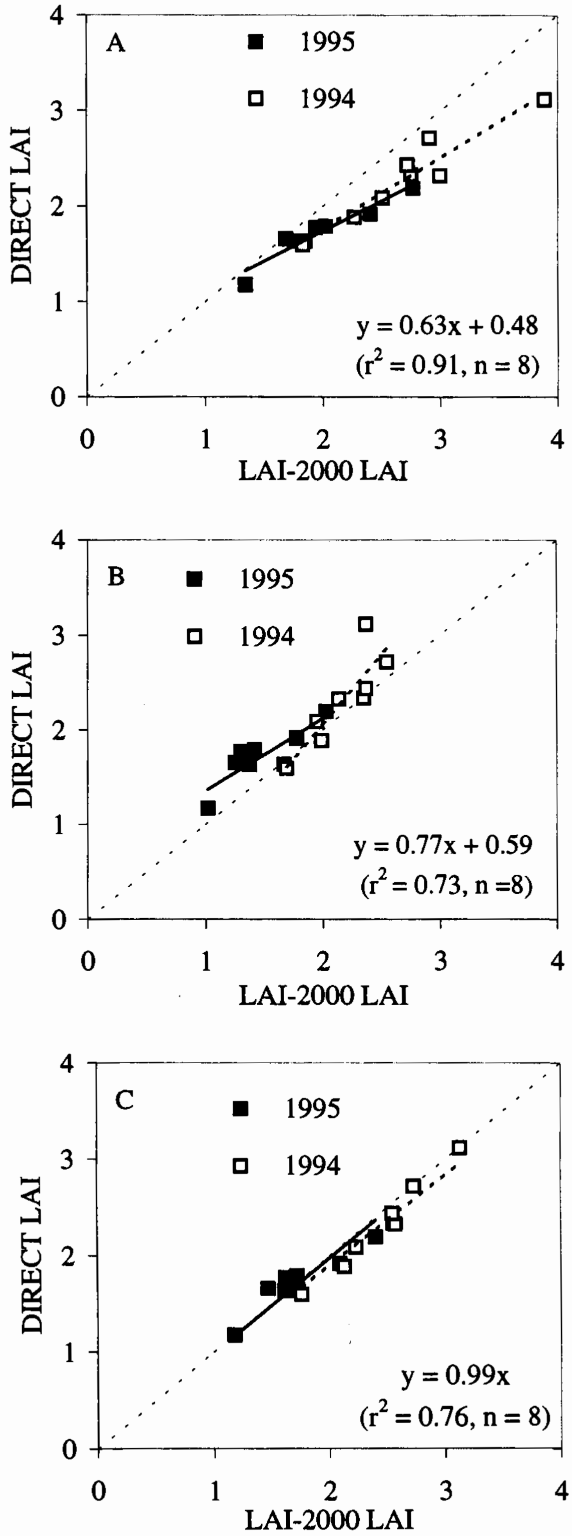

Fig. 5: Relationships between the average LAI-2000 data and the average direct LAI determinations made destructively, for a group of 5 vines, obtained in 1994 and 1995 in the "traditional" system, with the "parallel" protocol (**A**), the "diagonal" protocol (**B**) and the arithmetical average of both (**C**). Full lines represent linear regressions for 1995 and closed dotted lines the linear regressions for 1994. Equations are for 1995. The equation given in **C** corresponds to the regression without intercept.

cant difference at the 5 % level (SNEDECOR and COCHRAN 1957). A regression was then computed using all the data ($y = 0.74x + 0.29$, $r^2 = 0.94$, $n = 16$). This equation could be used as a calibration for the LAI-2000 data.

As in 1994, the "diagonal" protocol (Fig. 5 B) gave less satisfactory results and a lower correlation coefficient ($y = 0.77x + 0.59$, $r^2 = 0.73$, $n = 8$) than the other protocols. The linear regressions of the 1994 and 1995 data were also not significantly different (at the 5 % level). The linear regression equation of data in 1994 and 1995 was y = 0.93x + 0.31 (r^2 = 0.79, n = 16).

The arithmetical average between "parallel" and "diagonal" protocols again produced a good correlation (y = 0.73x + 0.47, r^2 = 0.88, n = 8). However, the equations computed in 1995 and 1994 were significantly different (at the 5 % level). When the linear regression was forced through zero (y = 0.99x, r^2 = 0.76, n = 8, Fig. 5 C), the correlation coefficient was lower, but still significant at the 1% level. As in 1994, the slope was very close to 1. There was no significant difference between the regressions forced through zero in 1994 and 1995 (at the 5 % level). The single regression equation was y = 0.96x (r^2 = 0.93, n = 16). The slope of this regression was not significantly different from 1 (Student test t = 1.31, n = 16). Consequently, with this method, the LAI-2000 determinations were in agreement with direct measurements of LAI. Therefore the LAI-2000 results can be considered a direct and accurate estimation of LAI.

The lyre training system: In 1994 and 1995, the same protocols used for the "traditional" system were applied to the lyre training system, but the results (not presented) were not satisfactory. A "parallel" protocol at a distance of 1.4 m gave the highest correlation coefficients. Although the coefficients were significant, they were unsatisfactory. In 1994 and 1995, the total range of LAI measured at different dates was low (2.2-3.5). This narrow range could be responsible for the poor correlation. Consequently in 1997, the LAI variability was artificially increased by removing leaves progressively and additional measures were made.

The results obtained in 1994, 1995 and 1997 are presented in Fig. 6. In 1997, the relationship between the LAI-2000 determinations and the direct measurements was linear with a high correlation coefficient (y = 1.1x - 0.6, r^2 = 0.99, n = 8). The data of 1994 and 1995 were distributed closely around the linear regression. Therefore a linear regression including all the data was calculated (y = 1.05x - 0.47, r^2 = 0.95, n = 22). The slope was close to 1, but the intercept was different from zero. The x-intercept was likely due to the contribution of perennial parts (shoots and posts) to the light interception and should not be ignored with training systems having large permanent structures. Thus the final protocol produces an accurate, but not direct estimation of vine LAI for lyre-trained vines.

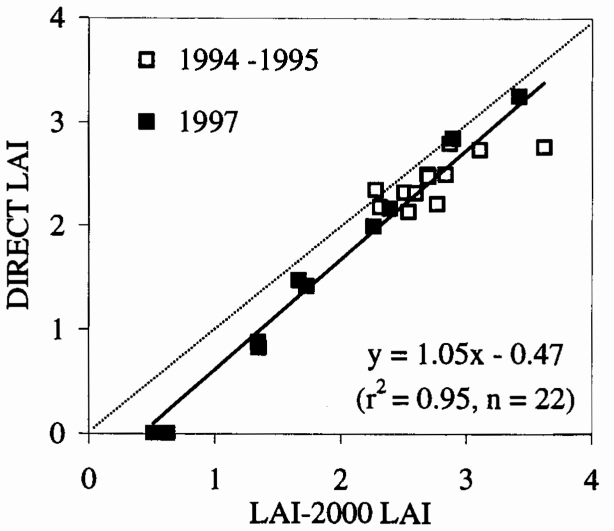

Fig. 6: Relationships between the average LAI-2000 data and the average direct LAI determinations made destructively, for a group of 5 vines, obtained in 1994, 1995 and 1997, in the lyre system with the "parallel" protocol. The full line represents the linear regression including all data. The equation describes the linear regression. The dotted line represents the 1:1 relationship.

Discussion

In this study the LAI-2000 performance under different vineyard conditions was evaluated and protocols for the best results are proposed. We observed that the LAI-2000 gives accurate estimation of LAI in a vineyard with two different plant densities and different canopy arrangements. However, the instrument is not able to measure the leaf area of a single vine of these dimensions. Indeed the relationships between single vine LAI-2000 determinations and values obtained by destructive measurements produced poor correlation coefficients. This result can be explained by the fact that each vine foliage to some extent overlaps neighbouring vines. Moreover, the 10 below canopy readings were made along a 2 m section for each vine, so that the first and the last readings were made opposite neighbouring vines. However, removing these readings and recomputing the data with the LICOR 1000-90 software did not improve the relationships (data not presented). The poor LAI-2000 performance recorded in our experiment is in agreement with previous studies performed in vineyards (Sommer and Lang 1994; Grantz and Williams 1995; Watanabe *et al.* 1997). In studies where the leaf area of single vines has to be determined, one should use other methods, e.g. the method described by Mabrouk and Carbonneau (1996). To be accurate, the LAI-2000 determinations have to be made on a group of several consecutive vines. In 1994, sample sizes of 3-5 vines were tested. Each sub-sample gave satisfactory results. However, the 4 or 5 vine samples allowed to get higher correlation coefficients.

Testing different sampling protocols indicated that the "diagonal" protocol with the field of view down the row underestimated LAI and the relationships between LAI-2000 determinations and direct LAI measurements were worse. These results are in agreement with other reports (LI-COR, 1989; Watanabe *et al.* 1997). The "parallel" protocol led to very satisfactory correlation coefficients, but the LAI was overestimated. This was also reported by LI-COR (1989), it is worse when the field of view faces the brightest part of the sky. In our experiments the view was facing west at sunset. Hicks and Lascano (1995) considered that these conditions result in an extended canopy shadow cast, which leads to an overestimation of LAI. Using only this protocol would require a local calibration as proposed by Grantz and Williams (1995). Finally, with a simple training system, a very good agreement between LAI-2000 and direct LAI determinations was obtained by combining the two types of sampling. This method allowed a direct and accurate LAI estimation which did not require any calibration. Our results support several reports on the use of two-azimuth protocols (Hicks and Lascano 1995; Welles and Cohen 1996).

Although the effects of year and cultivar were tested in a combined way, we did not find any significant differences in the relationships between LAI-2000 determinations and direct LAI measurements. Therefore we can assume that the geometry of plantation and the training system are more important than cultivar or year. This is further confirmed by our results with the lyre system. Indeed, with this training system, we could not find any simple protocol which allowed a direct estimation of LAI. The parallel protocol gave the best relationship with a slope close to 1. However, a calibration was required because the intercept differed from zero. This intercept is an estimation of the contribution of perennial parts and posts to the light interception. As in forest stands (ESCHENBACH and KAPPEN 1995), this contribution can not be neglected and is more important when LAI is low. In our lyre-trained vineyard, it was high because of the development of arms and cordons and of the size of the posts. With spur-pruned and cordon-trained vines, the contribution of perennial parts has to be evaluated for example by pre-bud burst LAI estimates. With the lyre system, the calibration was performed in 1997 by removing daily 25 % of the vine leaf area. The relationship between LAI-2000 determinations and direct LAI measurements was very good. This shows also that the LAI-2000 is sensitive enough to evaluate the intensity of leaf removal in some experiments such as mechanical leaf removal.

Conclusions

Our results demonstrate the good agreement between LAI-2000 determinations and the destructively measured LAI under various vineyard conditions for a small group of vines. A two-azimuth protocol is proposed for a direct LAI evaluation in a specified vineyard. Under different vineyard conditions, i.e. planting geometry, row orientation, we recommend that the protocol has to be confirmed and the contribution of perennial parts and trellis material is accounted. This can be done easily on two groups of vines by stepwise removing the leaves. Finally, our data support the interest in the gap fraction analysis for LAI determination if the assumption of foliage randomness is far to be met. The LAI-2000 is a good alternative to fastidious direct leaf area measurements and permits to evaluate more often this important parameter for viticultural research and experiments.

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