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AGROMETEOROLOGY - Article

Relationship between the normalized difference vegetation index and leaf area in vineyards

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ABSTRACT: In vineyards, the monitoring of leaf area is used to guide management practices in order to produce grapes with quality and enological potential. Remote sensing has been used to estimate leaf area by means of vegetation indices. This work aimed at determining the temporal evolution of the Normalized Difference Vegetation Index (NDVI) while associating it with leaf area of vineyards in the Serra Gaúcha region, Brazil. To this end, between 10 and 20 plants were evaluated monthly (September to May) in three vegetative seasons. NDVI data were obtained using the remote sensor Greenseeker while the following leaf area related parameters were obtained non-destructively: unit leaf area (ULA), average number of leaves per branch (NLB), plant leaf area (PLA), leaf area index (LAI) and chlorophyll index (CI). Data correlation was assessed by joint temporal analysis and Pearson correlations ($p < 0.05$). The results indicated that NDVI variation over time is coherent with the leaf area dynamics and expresses biomass variations due to phenology and management actions. The NDVI evolution pattern is described by a quadratic regression equation: the index increases rapidly at first (September to November), followed by a relative stabilization (December to February), and decreases in the final stage (March to May). The correlations were higher in the initial and final stages of the cycle, especially for NLB ($r = 0.73$ and 0.77), PLA ($r = 0.60$ and 0.61) and CI ($r = 0.48$ and 0.84), which are promising parameters for characterizing leaf area in vineyards by remote sensing.

Key words: NDVI, *Vitis vinifera*, Chardonnay, Serra Gaúcha region, Greenseeker.

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INTRODUCTION

Brazil is the fifth largest wine producer in the Southern Hemisphere and the Encosta Superior da Serra do Nordeste, known as Serra Gaúcha, is the most important producing region in the country and responsible for 85% of the national wine production (IBRAVIN 2017). The maximization of the relationship between quantity and quality is sought by balancing the leaf area (source) and fruit load (drainage) in vineyards intended for producing wine grapes (Mandelli et al. 2009). The leaf area index (LAI), defined as the total one-sided area of leaf tissue per unit ground surface area, is an important agronomical parameter related to photosynthetic capacity, water use, microclimate, canopy vigor, grape quality and enological potential (Drissi et al. 2009). The monitoring of leaf area and canopy development allows evaluating plant health conditions and guide management practices, including crop protection and canopy adjustments. In vineyards, summer pruning is a common leaf area management practice used to regulate canopy density and leaf distribution, thus promoting the aeration to reduce the likelihood of diseases (Mandelli et al. 2009), and increasing berry sun exposure to favor the concentration of phenolic substances (Bergqvist et al. 2001).

Currently, most of the methods available for monitoring LAI are based on manual measurement points, which are laborious, time-consuming and destructive in some cases (Fuentes et al. 2014). For this reason, viticulturists have few objective methods for quantifying, monitoring and mapping LAI in real time in the field (Fuentes et al. 2014; Johnson et al. 2003). Orbital and ground-based remote sensors have emerged as an important source of information on vegetative canopy through vegetation indices. The Normalized Difference Vegetation Index (NDVI) is linked to the quantitative biomass and can be used to monitor vegetative growth and to determine biophysical variables such as leaf area (Jensen 2007).

Studies developed in vineyards conducted in vertical training systems in France, Italy, Greece and the United States demonstrated the potential of NDVI to estimate leaf area index and vine vigor (Drissi et al. 2009; Mazzetto et al. 2010; Tardáguila et al. 2008; Stamatiadis et al. 2010; Bourgeon et al. 2017). However, studies on vineyards conducted in horizontal systems such as trellis, which is used in 67% of the grape production area in Rio Grande do Sul (Mello et al. 2013), are scarce. Thus, it becomes necessary to characterize and establish the relationship between the radiometric parameters of remote sensing products and the vine biophysical parameters as to increase the use of remote sensors in viticulture in Brazil and verify the potential use of vegetation indices in vineyard monitoring. The objective of this work was to determine the temporal evolution of the NDVI associating it with leaf area of Chardonnay grapevines in the Serra Gaúcha region, Rio Grande do Sul, Brazil.

MATERIAL AND METHODS

The study area consisted of commercial vineyards planted with *Vitis vinifera* cultivar Chardonnay in Veranópolis, in the Serra Gaúcha region, Rio Grande do Sul state, Brazil. According to Köppen, the regional climate is classified as type Cfb – temperate humid (subtropical) with average temperature below 22 °C in the hottest month (Alvares et al. 2013). The studied vineyards are North-South (NS) oriented and the soil was classified as a typical Dystrophic Lithic Udorthent. The grapevine canopies were managed in horizontal training systems, raised 1.8 m from the soil surface by wires, spaced from 2 m to 2.5 m between rows and from 1.5 m to 2 m between plants. The vine cycle was followed by the main phenological stages according to BBCH scale (Lorenz et al. 1995).

Between 10 and 20 plants were randomly selected for monthly sampling from September to May in three vegetative seasons (2014/2015, 2015/2016 and 2016/2017). Four branches, one per quadrant, were marked in each selected plant and used to determine the NDVI and the leaf area. The NDVI values were obtained with the Greenseeker Handheld HCS-100 Trimble sensor, a portable device that uses red (650 nm) and near-infrared (770 nm) radiation emission diodes to calculate the vegetation index. The sensor was manually positioned 60 cm above the vegetative canopy using an extensor bar (Fig. 1). The four NDVI snapshots were used to define the mean NDVI per plant each month.

Simultaneously to the acquisition of NDVI, parameters related to the vine leaf area were obtained non-destructively as follows: unit leaf area (cm^2) (ULA), calculated from the main vein length by a regression model; mean number of leaves per branch (NLB); total leaf area of the plant (m^2)

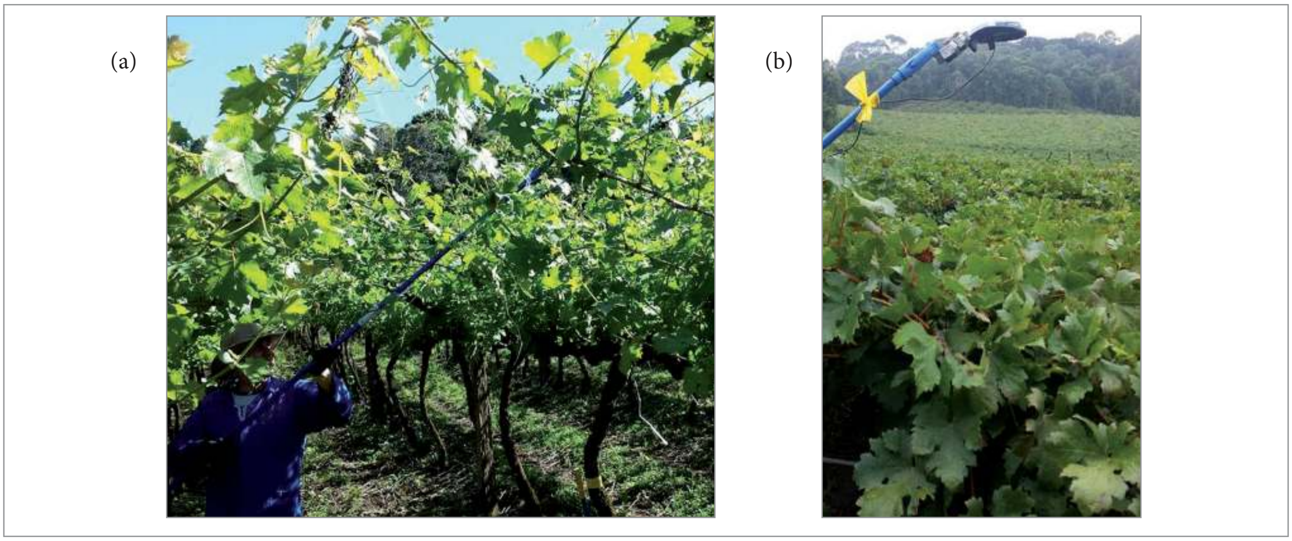

Figure 1. Data acquisition of Normalized Difference Vegetation Index (NDVI) with (a) remote sensor Greenseeker, and (b) the sensor position above the canopy in horizontal training system vineyard.

(PLA), given by multiplying the unit leaf area, average number of leaves and number of branches per plant; and leaf area index (LAI), estimated by dividing the plant leaf area (m^2) by soil area (m^2) (Anzanello and Souza 2015). The soil area was obtained by multiplying the average row spacing of the vineyards by the average spacing between plants in the row.

Leaf chlorophyll content was estimated indirectly and non-destructively with a handheld chlorophyll meter (ClorofiLOG, Falker Automação Agrícola). The chlorophyll meter used the transmittance values at wavelengths close to the absorption peaks of chlorophyll *a* (635 nm) and *b* (660 nm) for determining the chlorophyll index. The index was obtained in completely expanded leaves located in the intermediate portion of the marked branches (one per quadrant), simultaneously to the acquisition of the NDVI and leaf area data. The chlorophyll index and the unit leaf area were considered as parameters related to leaf development (leaf parameters), whereas the average number of leaves per branch, plant leaf area, and LAI were canopy parameters.

The NDVI behavior over time during the grapevine development cycle was determined from the mean values (± 1 standard error) of the vegetation index in the fortnights from September to May, for each evaluated vegetative season and for the average of the vegetative seasons (n = 10 to 50). To verify the NDVI trend over time, regression equations were adjusted and the one with the highest adjusted coefficient of determination (R^2) was selected. Average values of NDVI, number of leaves per branch, plant leaf area, LAI, unit leaf area, and chlorophyll index per plant were used to determine the parameters evolution over time in the evaluated vegetative seasons. The correlation between spectral data and leaf area parameters was evaluated by a joint temporal analysis and Pearson correlation ($p < 0.05$).

RESULTS AND DISCUSSION

The average NDVI varied between 0.45 and 0.85 in the evaluated vegetative seasons, expressing the high green biomass variation throughout the vine cycle (Fig. 2). The monitoring of leaf area with the remote sensor was possible from the first fortnight of September since Chardonnay is an early cultivar with estimated budding until September 10 in the study area (Mandelli et al. 2003). It was not possible to obtain NDVI data in the previous stage of the cycle (August) because the canopy porosity that resulted from the reduced number of leaves and unit leaf area, affected the signal received by the sensor.

The maximum NDVI values (0.81 to 0.84) were recorded in the second half of October and November, in the beginning of fruit set corresponding to the period between the phenological codes 73 (berries groat-sized, bunches begin to hang) and 77 (berries beginning to touch) in the BBCH scale (Lorenz et al. 1995) (Fig. 2). The lowest values (0.38 to 0.48) were observed in May for

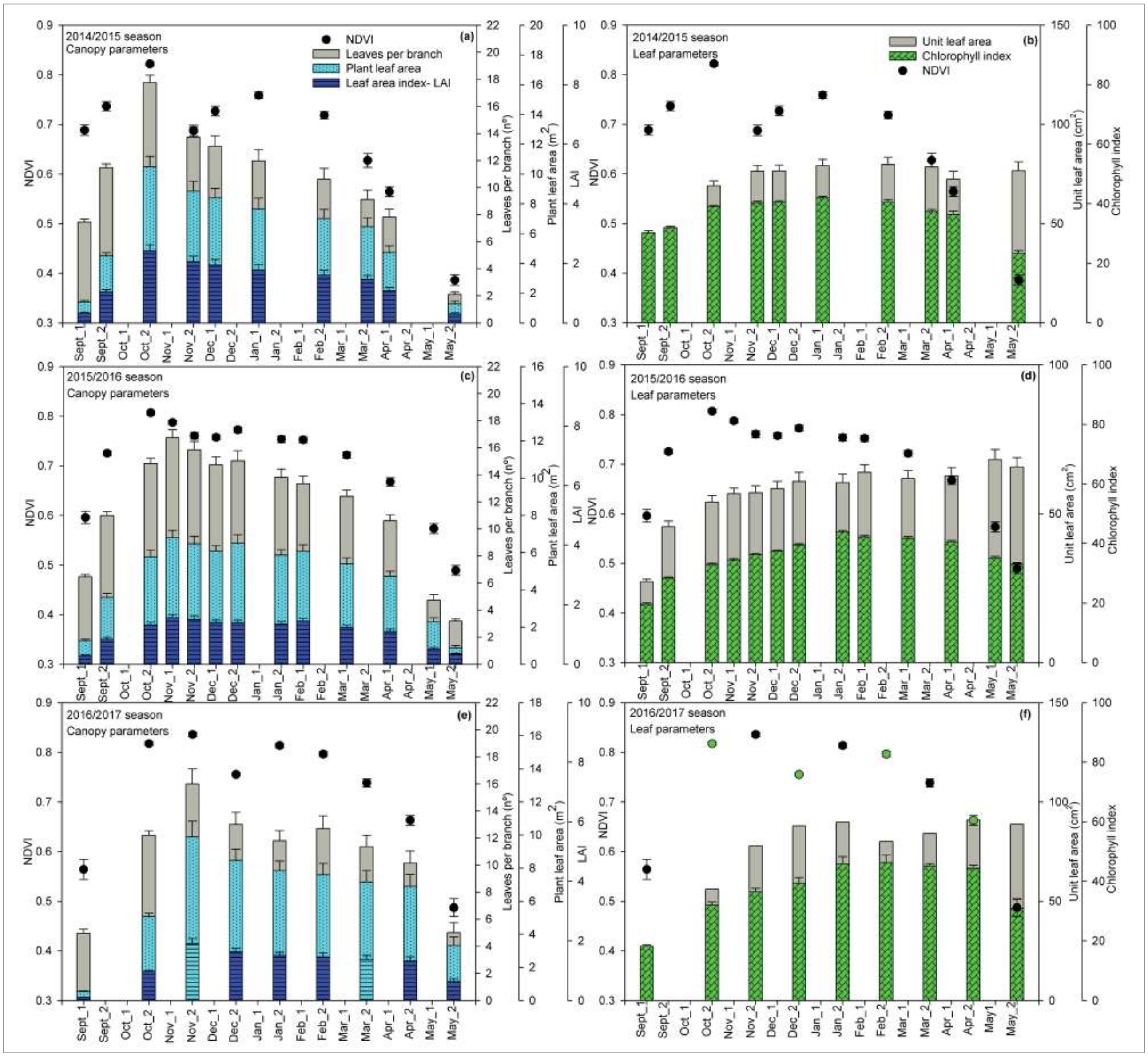

Figure 2. (a, c, e) Temporal evolution of Normalized Difference Vegetation Index (NDVI) and biophysical parameters number of leaves per branch, leaf area of the plant (m^2), leaf area index (LAI); (b, d, f) unit leaf area (cm^2) and chlorophyll index during Chardonnay vine cycle in Serra Gaúcha region, Brazil; (a, b) fortnight mean values (±1 standard error) from September to May in the vegetative seasons 2014/2015, (c, d) 2015/2016, and (e, f) 2016/2017.

phenological stage 95 (50% of fallen leaves), a period of senescence and leaf fall that characterizes the end of the vegetative cycle of the grapevine in the region.

Although the average NDVI values varied between the evaluated vegetative seasons, the index evolution in the cycle was coherent with the biophysical parameters related to the vegetative canopy expansion (Figs. 2a, 2c, 2e), as well as unit leaf growth and development (Figs. 2b, 2d, 2f). In the first half of September, when the plants had 7.5 leaves per branch on average and LAI less than 1, the average NDVI was 0.63. The NDVI values tended to increase over time, from September to the second fortnights of October (2014/2015 and 2015/2016) (Figs. 2a, 2c) and November (2016/2017) (Fig. 2e), when it peaked (0.81 to 0.84). The NDVI peaks were recorded in the fortnights when the number of leaves per branch (16 to 18), plant leaf area (6 to 7 m^2) and LAI (1.6 to 2.4) peaked as well, demonstrating the similar evolution of spectral and leaf area data. In 2016/2017, although the NDVI (0.84) peaked in the second half of November, the index values had already reached 0.80 in the second half of October (Fig. 2e), as observed in other seasons, so that rapid incremental values at the beginning of the cycle (September to October) is characteristic of NDVI temporal profiles of vineyards.

Tardáguila et al. (2008) studied a vineyard (cultivar Tempranillo) in Spain using the Greenseeker remote sensor and reported peaks between 0.65 and 0.75 at the beginning of berry ripening (phenological stage 81) while, in France, Bourgeon et al. (2017) observed NDVI peak of 0.70 for Chardonnay in the phenological stage 75 (berries pea-sized). The NDVI peak obtained in this study was higher compared to the values cited in the literature due to greater vegetative vigor in horizontal training systems compared to vertical ones, as already pointed out by Junges et al. (2017).

After peaking, the NDVI values (0.70 to 0.76) decreased, generally during two fortnights (until the second half of November) in 2014/2015 and 2015/2016 (Figs. 2a, 2c) and until the second half of December in the 2016/2017 vegetative season (Fig. 2e). The NDVI indicated that the green biomass of the vine canopy decreased, which was associated with the decreasing average number of leaves per branch (between 13 and 15) that resulted, especially, from the summer pruning. The summer pruning, which consists of removing some shoots and leaves, is a management practice conducted to reduce vigor and promote balance between the vegetative and productive parts of the vine (Mandeli et al. 2005). Bourgeon et al. (2017) also observed decreasing NDVI values (0.70 to 0.66) after two pinching backs were done in Chardonnay vineyard to reduce foliage occupation. The NDVI indicated the green biomass reduction that resulted from the management actions aimed at reducing the leaf area, demonstrating the potential of the index to detect interventions in the vegetative canopy.

After the summer pruning, the NDVI increased but did not peak. Thus, from December to February, mean NDVI values remained stable and close to 0.75, except for 2016/2017 season, when they reached 0.80 in January and February (Figs. 2e and 2f). In this stage of the grapevine cycle that includes the phenological stages of softening of berries (phenological stage 85), harvest (between the second fortnight of December and the first of January), and the beginning of the post-harvest period (phenological stage 91), the biophysical parameters related to the leaf area of the vegetative canopy were also stable (Figs. 2a. 2c and 2e). The chlorophyll index followed the expanding unit leaf area, so that the values were lower (between 19 and 31) at the beginning of the cycle (first half of September), increasing until January and February, when peaks were recorded (chlorophyll index between 43 and 46 and unit leaf area between 80 and 90 cm^2) (Figs. 2b, 2d, 2f). Likewise, Giovannini (2005) reported that vine leaves generally reach 75% of the maximum size in early summer whereas growth stabilizes in January.

From March onward, NDVI gradually decreased over time, reaching a minimum (between 0.38 and 0.49) in May. The average number of leaves per branch (2 to 5), plant leaf area, LAI (less than 0.5), and chlorophyll index (between 22 and 33) decreased as well (Fig. 2). The decreasing NDVI values at the end of the cycle were expected due to the senescence and yellowing of the grapevine leaves. Vines, like other temperate fruit trees, have a deciduous habit, e.g., they go through a dormancy period due to the decreasing air temperature in the autumn-winter period (Mandelli et al. 2009). The results show that the NDVI reflected the decrease of green biomass in the vegetative canopy due to senescence and leaf fall, agreeing with Bourgeon et al. (2017) conclusion that the NDVI is used in vineyards especially to characterize the global vegetation status, being often correlated to foliage quantity.

The NDVI temporal profiles varied every fortnight, especially at the beginning and at the end of the cycle, which expresses leaf area differences between vegetative seasons and may be associated with management practices and variability of the meteorological conditions (plant-environment interaction). However, despite the variability, the NDVI profile was similar over time for all evaluated seasons (Fig. 3). The mean temporal evolution of the NDVI can be described by a quadratic regression equation (Fig. 3), allowing identifying three stages that characterized the index variation during the cycle. The first stage corresponded to the September/October/November quarter, shows a rapid NDVI increase (Fig. 3) represented by the ascending portion of the curve.

The second stage was defined by the point of maximum inflection of the upward curve of the values (second half of November) (Fig. 3) and comprised the December/January/February quarter. In this stage the vegetation index was relatively stable, although with a slightly decreasing tendency according to the quadratic equation.

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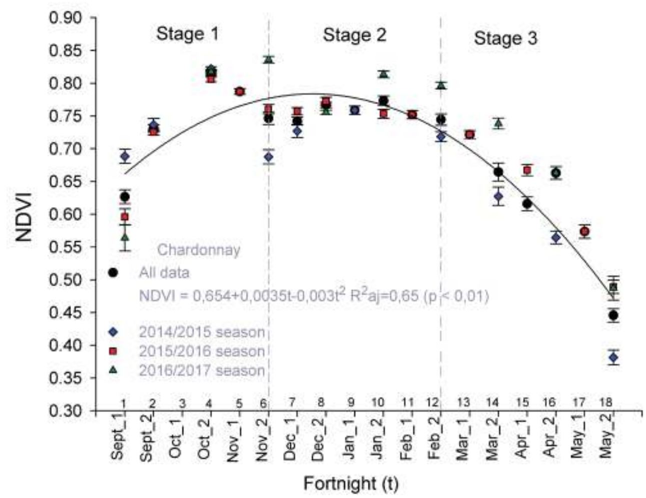

Figure 3. Regression equation to define temporal evolution of Normalized Difference Vegetation Index (NDVI) during Chardonnay vine cycle in Serra Gaúcha region, Brazil; fortnight mean values (±1 standard error) from September to May in vegetative seasons 2014/2015, 2015/2016, 2016/2017 and in data set.

In the third stage, in the March/April/May quarter, the equation shows the gradual decrease of the mean NDVI values (Fig. 3), characterizing the end-of-cycle period. The quadratic model described the NDVI evolution over time adequately, as already verified in studies characterizing the grapevine cycle. Ballesteros et al. (2015) also used quadratic regression equation to correlate LAI and canopy volume to the degrees-day accumulated during the cycle of grapevine cultivars Tempranillo and Airen in Spain. Drissi et al. (2009) established a quadratic correlation between NDVI and LAI in vineyards in France. Johnson et al. (2003) reported a linear relationship between NDVI obtained by orbital remote sensor and LAI in vineyards in the United States; however, they used sprouting data at harvest, not considering the post-harvest period, when both parameters decrease. Rinaldi et al. (2013) also used quadratic models to correlate canopy volume to vine phenological stages using spectral data.

The correlations between NDVI and biophysical variables, when considering the data set obtained throughout the grapevine cycle, were positive, especially for the average number of leaves per branch (Fig. 4a), plant leaf area (Fig. 4b), and LAI (Fig. 4c). The NDVI was not correlated with unit leaf area (Fig. 4d), as this biophysical parameter increases gradually over the cycle until peaking, and then stabilizes. At the end of the cycle, the decreasing NDVI was associated with the decreasing number of leaves per branch, and not with the unit leaf area, since this does not change during senescence. The correlation between NDVI and chlorophyll index was positive (Fig. 4e), although lower than the variables related to leaf area of the vegetative canopy. Similarly, Bourgeon et al. (2017) indicated that NDVI appears as a combination of the quantity of vegetation and its physiological activity: first, the decrease of physiological activity is compensated by the foliage occupation; then, when foliage occupation becomes stable or decrease, the physiological activity acts on NDVI values (Bourgeon et al. 2017).

The results indicated that NDVI is strongly associated with the green biomass of the canopy of vines and it can be considered more comprehensive estimate of the canopy leaf area because of the sensor position (Fig. 1). Therefore, the vegetation index has the potential to generate information for vineyard monitoring purposes and for qualitative and quantitative evaluation of plant development.

The correlation between variables in the stages defined by the regression equation shows that the association between NDVI and leaf area were positive in the initial stage (September to November) (Fig. 4f, 4g, 4h, 4i, 4j), indicating proportional increase of vegetation index and parameters. In this stage, the average number of leaves per branch had the highest correlation with NDVI because the biomass produced by a plant is more closely associated with the total size of its assimilative system than with the photosynthetic rate of single leaves. These results are in accordance with studies showing that the Greenseeker sensor can be employed to characterize vine vigor during growth stages (Drissi et al. 2009).

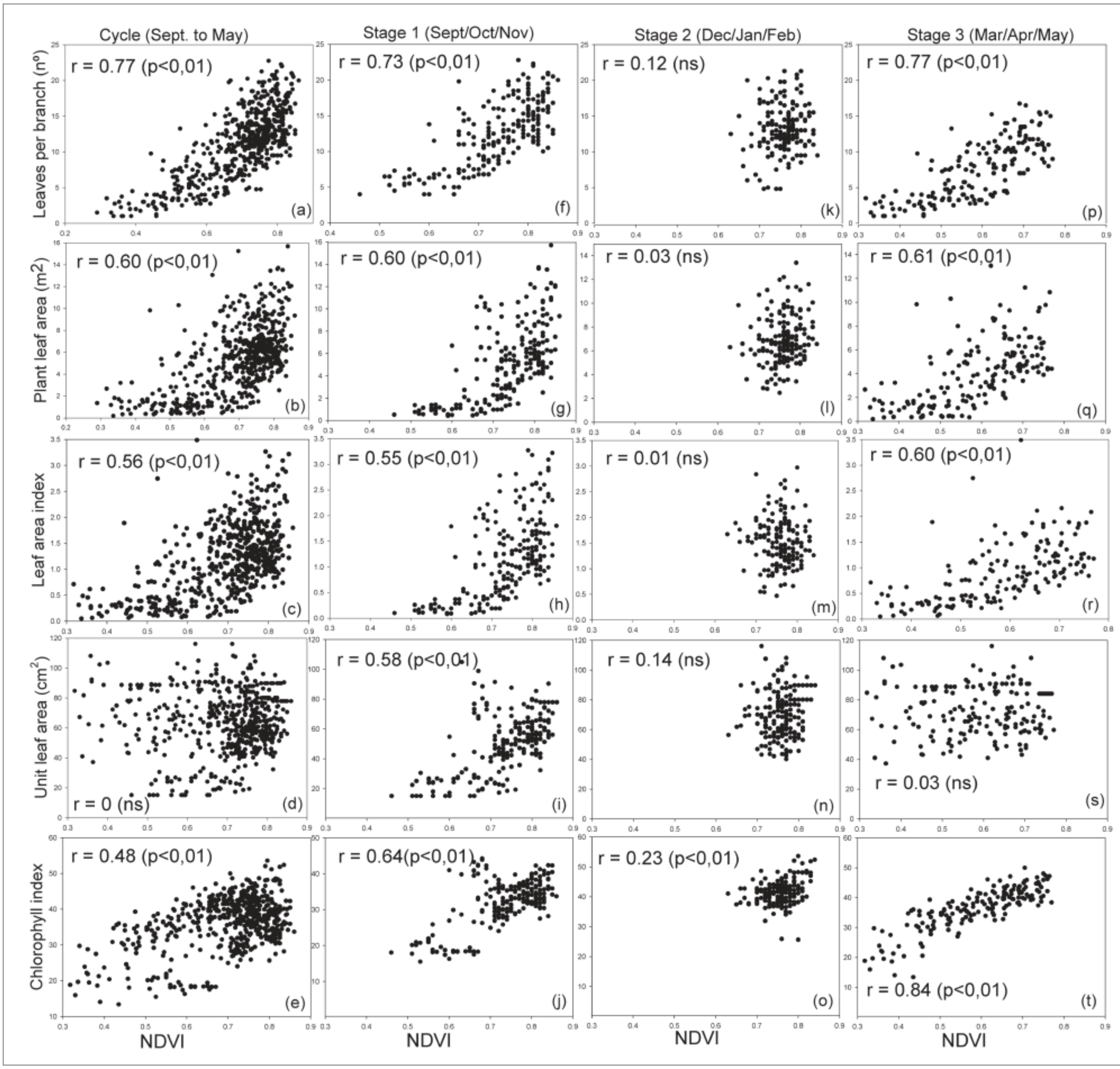

Figure 4. Pearson correlation between Normalized Difference Vegetation Index (NDVI) and biophysical parameters (a, f, k, p) number of leaves per branch; (b, g, l, q) leaf area of the plant (m^2); (c, h, m, r) leaf area index (LAI); (d, i, n, s) unit leaf area (cm^2); and (e, j, o, t) chlorophyll index in (a, b, c, d, e) cycle (September to May); and in the stages (f, g, h, i, j) 1 (September to November); (k, l, m, n, o) 2 (December to February) and (p, q, r ,s, t) 3 (March to May) of the Chardonnay vine cycle (seasons 2014/2015, 2015/2016 and 2016/2017) in Serra Gaúcha region, Brazil.

Although lower, compared to the previous stage, only the NDVI and chlorophyll index were significantly correlated in the second stage (December to February) (Fig. 4o). The lack of correlation between NDVI and other leaf area biophysical parameters arises from the probable lack of linear relationship between the variables. In this stage, variations of the biophysical parameters are not accompanied by proportional variation of the NDVI values, whose stabilization may indicate saturation of the vegetation index. Such saturation occurs because the vegetation reflectance in the red and near-infrared wavelengths does not increase linearly with increasing leaf area. Junges et al. (2017) pointed out the NDVI saturation in temporal NDVI profiles of Chardonnay and Cabernet Sauvignon in the same region. Drissi et al. (2009) indicated that the NDVI response to gap fraction (the proportion of transmitted light that is not blocked by foliage) follows a sigmoidal trend that reveals the lower sensitivity of the index when vineyard gap fraction is > 80%.

The correlations between NDVI and biophysical parameters were again significant in the third stage of the cycle (March to May), except for the unit leaf area (Fig. 4s). The vegetation index decrease was proportional to the reduction of the number of leaves per branch (Fig. 4p), plant leaf area (Fig. 4q), LAI (Fig. 4r) and, especially, the chlorophyll index, parameter greatly correlated with the NDVI in this stage of the cycle (Fig. 4t). The correlation between NDVI and leaf area parameters in this final stage of the cycle indicates its potential as an indicator of post-harvest leaf area maintenance. This information is important for temperate fruit trees such as vines because the presence of leaves at the end of the cycle is related to the accumulation of tissue reserves, which favors the initial growth of shoots in the next cycle (Anzanello and Souza 2015).

Finally, it is important to consider that leaf area estimates from the main vein length, such as those performed in this study, while having the advantage of being non-destructive, measuring the leaves is time-consuming and labor-intensive. In addition, the leaves correspond to samples and, in general, empirical models often underestimate leaf area in very dense canopies (Lopes and Pinto 2005). In turn, through indices obtained by remote sensing, all vegetation information is summarized to only one numerical value, which in the case of portable active remote sensors, can be obtained in the field and in real time to allow fast extraction of information related to vine canopy. The Greenseeker sensor procedure is simple with easy real-time applicability. Remote sensing techniques can provide plant development information in order to promote canopy adjustment in vineyards.

CONCLUSION

In vineyards, the temporal NDVI profile is consistent with the dynamics of the biophysical parameters related to the leaf area and expresses the varying green biomass throughout the vine cycle.

The NDVI indicates reduction of green biomass resulting from management practices that aim to reduce the leaf area, thus demonstrating the potential of the index for detecting the interventions in the vegetative canopy.

The temporal NDVI evolution of vineyards in horizontal training systems is described by a quadratic regression equation and characterized by an initial stage of rapid NDVI increase from September to November, followed by a relatively stable stage between December and February and, finally, a decrease in the March/April/May quarter.

The NDVI is correlated with biophysical parameters related to grapevine leaf area, especially with the average number of leaves per branch. The correlations are higher in the initial and final stages of the cycle, especially for the average number of leaves per branch, plant leaf area, and chlorophyll index. These parameters are promising for characterizing vineyards and may be used in the future to adjust models of leaf area estimation, contributing to the advance of remote sensing applications in viticulture.

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AUTHORS' CONTRIBUTION

Conceptualization, Junges, A. H. and Fontana, D. C.; Methodology, Junges, A. H.; Investigation, Junges, A. H. and Lampugnani, C. S.; Resources, Junges, A. H. and Lampugnani, C. S.; Writing – Original Draft, Junges, A. H.; Writing – Review and Editing, Junges, A. H. and Fontana, D. C.; Supervision, Junges, A. H.

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