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Temporal stability of an NDVI-LAI relationship in a Napa Valley vineyard

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Abstract

Remotely sensed values for normalised difference vegetation index (NDVI) were derived periodically from high-resolution Ikonos satellite images during the 2001 growing season, and compared with ground measurements of vineyard leaf area index (LAI) during that same period. These two derived variables were strongly related in six vineyard blocks on each of four occasions (R^2 = 0.91 to 0.98). Linear regression equations relating these two derived variables did not differ significantly by time-step, and a single equation accounted for 92 per cent of the variance in the combined dataset. Such temporal stability in that relationship opens the possibility of transforming NDVI maps to LAI units, at least on a localised basis, and minimising (or even eliminating) subsequent ground calibration. This reduction in fieldwork would then decrease information cost for viticulturists who wish to monitor LAI sequentially within season, or who wish to track year-to-year changes in climax LAI with a single image collected annually. To take advantage of this cost reduction, temporal consistency in spectral data values comprising NDVI must be assured. This present paper addresses that issue.

Keywords: Vitis vinifera *L., remote sensing, canopy monitoring, vineyard leaf area, leaf area index, spectral vegetation indices, NDVI, Ikonos satellite*

Introduction

An increasing number of technologies are becoming available for characterising the nature and understanding the sources of vineyard variability (e.g. Bramley 2001). Of these technologies, remote sensing can be used to map and monitor vineyard canopy density (Wildman et al. 1981, Johnson et al. 1996, Lamb et al. 2001, Hall et al. 2002). Observations during canopy expansion can detect problems related to water and nutrient stress (Lamb 1999), while later-season imagery can support harvest management (Johnson et al. 2001a).

Agricultural remote sensing products are frequently based on so-called spectral vegetation indices (SVIs), formed as various combinations of visible and near-infrared (NIR) spectral channels of digital imagery (Schowengerdt 1997). SVIs are *radiometric* variables that are useful for mapping *relative* variations in canopy density. One common SVI is the normalised difference vegetation index (NDVI), formulated as (NIR-red)/(NIR+red). Many commercial winegrape growers in coastal California are now using NDVI imagery, generally acquired at maximum foliar expansion, to delineate management zones, identify problems, and re-develop properties (Carothers 2000, Aho 2002).

Studies in agricultural settings have shown that SVIs are sensitive to plant canopy leaf area index (LAI; m^2 leaf area/m^2 ground area) and absorbed photosynthetically active radiation (Asrar et al. 1984, Wiegand et al. 1991, Daughtry et al. 1992). Vineyard LAI is determined by vine size and planting density. Ground-based and theoretical studies have shown that the NDVI and other SVIs are sensitive both to vine size (Dobrowski et al. 2002) and fractional cover (Carlson and Ripley, 1997), which in vineyards is strongly related to planting density. Remote sensing analyses have confirmed that SVIs are related to vineyard LAI (Johnson et al. 2001b, 2003, Dobrowski et al. 2002).

Vineyard canopy density is related to fruit ripening rate (Winkler 1958), infestation and disease (Wildman et al. 1983, English et al. 1989), water status (Smart and Coombe 1983), yield (Clingeleffer and Sommer 1995, Baldy et al. 1996, Dry 2000), fruit characteristics and wine quality (Smart 1985, Jackson and Lombard 1993, Mabrouk and Sinoquet 1998). Derived as the ratio of canopy leaf surface area to vineyard ground surface area, LAI can be regarded as a *state* variable that describes canopy density in *absolute*, physical terms. LAI maps, alternatively expressed in terms of leaf area per vine or per metre of row (after Johnson et al. 2001b, 2003), may provide a more intuitive canopy management tool than maps presented in SVI units. In addition, LAI and related maps can be combined with other spatial datasets to derive assessments such as shoot balance (after Iland et al. 1995, Smart 2001) and vineyard water relations (Nemani et al. 2001).

While operational adoption of SVI-based products is

Table 1. Description of vineyard blocks used for study. Mean LAI on 2001 measurement dates as shown (standard error in parentheses).

Block	Vine spacing (m)	Row spacing (m)	Plot size (m^2)	Training[a]	Cultivar[b]	Age (years)	LAI 30 May	LAI 3 July	LAI 1 Aug	LAI 27 Sept
1	1.5	1.8	24.3	n	SB	1	0.26 (0.04)	0.55 (0.08)	0.60 (0.06)	0.65 (0.07)
2	1.8	3.7	60.0	n	CS	27	0.31 (0.12)	0.49 (0.22)	0.49 (0.20)	0.54 (0.23)
3	2.4	3.7	79.9	S	CF	20	0.82 (0.07)	0.90 (0.04)	0.95 (0.04)	0.91 (0.09)
4	3.0	1.8	48.6	V	CS	9	1.08 (0.14)	1.58 (0.20)	1.97 (0.28)	1.85 (0.24)
5	1.5	2.7	36.5	S	CF	10	1.47 (0.14)	1.38 (0.07)	1.42 (0.09)	1.46 (0.09)
6	1.8	3.0	48.6	Y	CS	9	1.62 (0.04)	1.83 (0.08)	1.92 (0.13)	1.95 (0.11)

[a] S (sprawl), V (vertical), Y (split), n (none)
[b] SB (Sauvignon Blanc), CS (Cabernet Sauvignon), CF (Cabernet Franc)

widening, implementation of LAI mapping will involve a comparison of marginal information costs with respect to the benefits suggested above. Accordingly, the goal of this present study was to provide additional insights into these potential costs. To achieve that goal, high-resolution satellite remote sensing was used to monitor LAI in several Napa Valley vineyard blocks through the 2001 growing season. Temporal stability of the NDVI-LAI relationship was then analysed.

Methods

Study area

The study area was the To-Kalon commercial vineyard of the Robert Mondavi Winery (Oakville, Calif.). The ~500 ha vineyard is located in California's mild climate Napa Valley at ~38°25′N/122°25′W, growing mainly red grape varieties on clay loam soils. The vineyard is subdivided into many blocks of differing planting density, trellis system, age and cultivar. Maximum LAI, generally less than 3 m^2 leaf area per m^2 of vineyard floor (between-row spaces included), is attained by late July and persists through harvest in mid- to late September. Shoots are pruned annually to the second node during dormancy. Vegetation understory is generally dry by early June, and may be ploughed into the soil at that time. Phenological stages at To-Kalon during 2001 were observed, on average, as follows: budburst (24 March), flowering (16 May), veraison (19 July) and harvest (15 September).

LAI measurements

During the 2000 growing season (16 August), a calibration exercise was performed to relate main shoot lengths to total leaf area per shoot. Five sample plots were established in different vineyard blocks at To-Kalon. Each plot was represented by five vines (a centre vine and two vines in each adjacent row) as in Figure 1. Lengths were measured and recorded for two randomly selected shoots per sample vine. Alternate leaves were then removed from each sampled main shoot, and all leaves were removed from lateral shoots. The leaves were immediately bagged and placed in a cooler, then transported to a laboratory for refrigerated overnight storage. The following day, an electronic meter (Model LI-3000, LI-COR, Inc., Lincoln, Nebr.) was used to measure the area of all sampled leaves. Total leaf area per shoot (m^2), including leaves on lateral shoots, was related to main shoot length (m) as:

$$LA_{shoot} = -0.036 + 0.301 \times \text{shoot length} \quad (R^2 = 0.64;\ n = 50;\ P < 0.01) \qquad (1)$$

During the 2001 season, shoot length measurements were used to estimate LAI in six vineyard blocks on four dates ranging from post-flowering to harvest (Table 1). Measurement plots were sampled as illustrated in Figure 1. Four of the six plots were the same as those used to collect the data for equation (1). Trellis types included vertical shoot position, lyre (split) and 'California sprawl'. (In the latter configuration, shoots grow vertically through two wires positioned approximately 30 cm above the cordon arms, thereafter sprawling in various directions.) In addition, two of the plots were completely untrained. No hedging was performed in any of the plots.

On each date, the total number of shoots per vine was counted and lengths of five randomly selected main shoots were measured on each vine. Equation (1) was

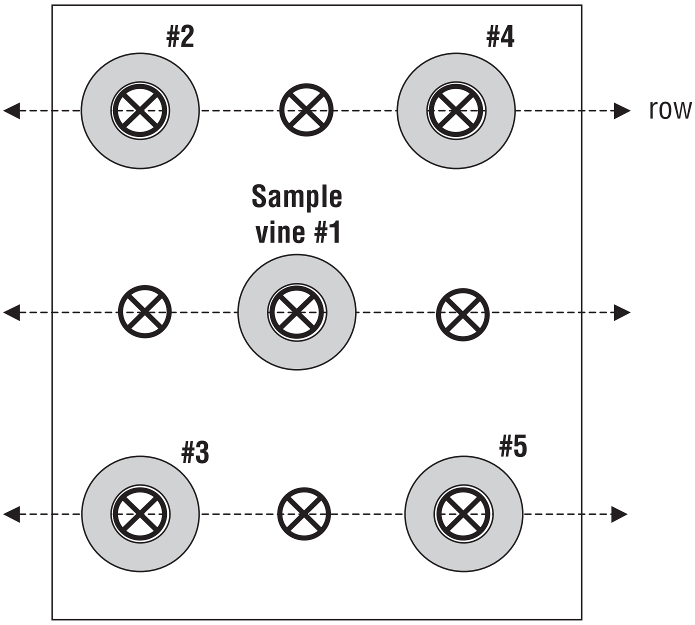

Figure 1. Layout of plots used for shoot length measurement. Five vines were sampled per plot, as indicated.

Table 2. Ikonos satellite scenes used in analysis. Corresponding values for solar elevation (above horizon) and solar azimuth (clockwise from north) provided.

Date	Time (GMT)	Scene ID	Solar Elevation	Solar Azimuth
03 June 2001	19:20	PO67786	71°	144°
30 June 2001	19:04	PO67785	69°	131°
28 July 2001	19:25	PO67818	67°	147°
04 Sept 2001	19:10	PO79011	56°	154°

used to calculate leaf area per sampled shoot. Leaf area per vine was derived as the product of mean leaf area per shoot and number of shoots. Finally, mean leaf area per vine was divided by the ground area allocated to each vine (as the product of between-vine distance within row, and distance between rows) to estimate block LAI on each occasion. This measurement approach was fairly rapid, consuming only about five minutes per block, and required no specialised equipment or supplies.

At the end of the 2001 season, ground coordinates of the centre of each measurement plot were recorded to sub-metre accuracy with differential GPS. Additional control points were taken at road intersections and other conspicuous locations to verify proper alignment with imagery.

NDVI measurements

Four Ikonos multispectral satellite scenes were procured from Space Imaging, Inc. (Thornton, Colo.), corresponding to the following dates: 3 June, 20 June, 28 July and 4 September, 2001 (Table 2). The 11 km × 11 km images were collected in the visible and NIR spectral regions at four metre spatial resolution under clear sky conditions near 12:00 noon local time. Digital counts in the red (632–698 nm) and NIR (757–853 nm) channels were converted to at-sensor radiance (mW/cm^2 sr) by applying

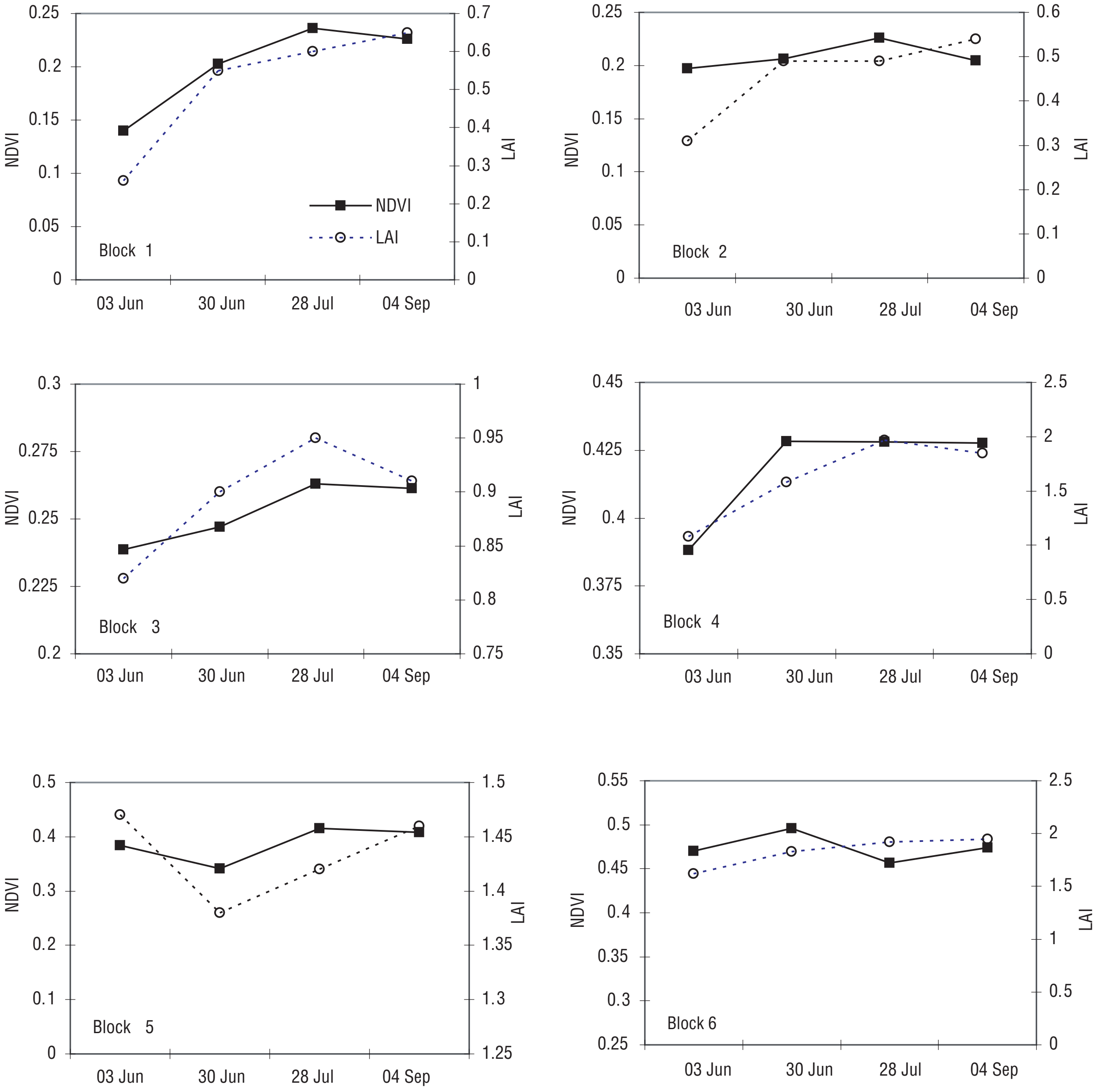

Figure 2. Temporal progression of mean NDVI and mean LAI in each study block. Image acquisition (NDVI) dates shown on x-axes.

the laboratory-derived radiometric calibration coefficients of Peterson (2001). The images were registered, by nearest-neighbour resampling (input pixel values maintained), to the California State Plane Coordinate System (Zone II-3301, North American Datum 1983, GRS 80) by scene-to-scene registration with a one-metre resolution Digital Ortho Quarter Quad (US Geological Survey). The radiance values were then converted to NDVI on a per pixel basis. The specific 4 m × 4 m image pixel containing each ground measurement plot centre was identified by GPS coordinates. To suppress the effects of sensor-induced random noise, mean NDVI for a nine pixel grouping (3 × 3 pixel 'box' about the centre pixel) was extracted in each case.

Statistical analysis

Block NDVIs on each date were paired with the most contemporaneous LAI measurement set to represent four time steps. LAI data were collected within three days of each of the first three image acquisitions, and 23 days after the fourth acquisition. Linear regression equations of the form NDVI = b × LAI + a were developed to analyse data on both a time-step and seasonal basis. Tests were performed to evaluate coefficient significance, and 95% confidence intervals were generated. Analysis of variance (ANOVA) was used to test for an influence of image acquisition date on the combined NDVI dataset.

Results and discussion

The temporal trend in NDVI was compared with the LAI trend in each block (Figure 2). LAI trends reflected any foliar expansion that occurred from post-flowering onward. Also captured were the effects of canopy management activities such as suckering and shoot removal, most pronounced in block 5. Blocks 3 and 4 showed some late-season LAI decline, possibly related to leaf drop. Qualitatively speaking, the NDVI appears to capture temporal differences in LAI. Here, it is worth noting that apparent NDVI will be influenced by the presence of green understory vegetation in the form of cover crop or volunteer plants. Imagery collected during very early season such as pre-flowering (not attempted here) may thus be relatively insensitive to vine expansion unless understory growth is precluded or removed, or additional image collection or image processing strategies are applied (e.g. Lamb et al. 2001) to isolate and delete the understory signal.

Results were also examined on a per-time-step basis. Goodness of fit (R^2) ranged from 0.91–0.98 across time-steps (Table 3). Slope (b) was significantly different from zero in all cases ($P < 0.01$ or better). Range in b among time-steps was 0.159–0.217, although these were statistically inseparable. Intercept values (a) were also significantly different from zero in all cases ($P < 0.05$ or better), and ranged from 0.078–0.143 (statistically inseparable). This offset is to be expected, as bare soils at To-Kalon have an NDVI of approximately 0.10 (Johnson et al. 2003). Although a temporal influence between LAI and NDVI is locally evident within individual blocks (Figure 2), ANOVA results indicated that image date was not a significant predictor of NDVI in the global dataset. Pooled time-steps were described by the relationship NDVI = 0.188 (LAI) + 0.113 ($R^2 = 0.92$, n = 24). This relationship can be inverted to express LAI as a function of NDVI (Figure 3).

These results reinforce findings of Montero et al. (1999) (LAI 1.0–3.4) and Johnson et al. (2003) (LAI 0.4–2.8), wherein linear relationships between NDVI and vineyard LAI were observed. As well, Dobrowski et al. (2002) reported similar goodness-of-fit based on linear and logarithmic equations for LAI of range 0.4–2.2. It is probable that the linear nature of this relationship is due, at least in part, to relatively low values for LAI (e.g. Nemani and Running 1989). NDVI tends to saturate at higher LAI and thus, for hotter climate, unpruned or minimally pruned sites, a decline and eventual loss of NDVI sensitivity would be expected.

This present investigation contained several sources of uncertainty related to both ground and remote observation.

1. Vine-to-vine differences introduced uncertainty in ground-based LAI measurement (see Table 1 standard errors). This effect was greatest for block 2, which contained older plants of widely varying vigour.
2. LAI estimation involved an equation relating shoot length to late-season total leaf area per shoot, which included leaves on the main and lateral shoots. This equation would tend to overestimate leaf area during the earlier part of the season, prior to lateral development.
3. A size discrepancy existed between the ground measurement plots, which ranged from 24 to 80 m² (Table 1), and the remote sensing integration area (144 m² throughout). Vineyard variability, due to differences in site-specific factors such as soils, may have introduced measurement bias at the block level.
4. Temporal discrepancy between LAI and NDVI

Table 3. Regression results of the form NDVI = b × LAI + a, at four time-steps during the 2001 growing season. Superscripts indicate significant difference from zero. Coefficient 95% confidence limits, sample size (n) and R^2 also shown.

Time-step	b	95% lower	95% upper	a	95% lower	95% upper	R^2	n
1	$0.217^{0.01}$	0.125	0.308	$0.102^{0.05}$	0.005	0.200	0.91	6
2	$0.215^{0.001}$	0.155	0.276	$0.078^{0.05}$	0.004	0.153	0.96	6
3	$0.159^{0.01}$	0.098	0.220	$0.143^{0.01}$	0.060	0.226	0.93	6
4	$0.188^{0.001}$	0.146	0.229	$0.103^{0.01}$	0.048	0.159	0.98	6

measurement per time-step may have introduced additional errors related to differences in phenology and management practices. However, the difference of just a few days for the first three time-steps was probably insignificant. The larger difference for the fourth time-step was potentially significant due to leaf drop, yet is not readily apparent in Figure 2.

5. Red and NIR radiances are sensitive to sun angle, which varied as reported in Table 2. Irradiance is directly related to solar elevation, and surface-reflected radiance in addition varies with scene shading by interaction of solar elevation, azimuth, and scene geometry (e.g. vineyard row direction). Though imperfect, the ratio formulation of NDVI provides a degree of resistance to this effect (Johnson 1994).
6. NDVI can be influenced by atmospheric turbidity (Huete and Jackson 1988). It is reasonable to assume that such differences existed among dates, but no specific measurements were made nor corrections applied.

Despite these sources of potential error, present results indicate a remarkably stable relationship between LAI and NDVI for these particular study blocks over the course of the season (Figure 3). It might then be reasonable to repeatedly apply a single NDVI-LAI conversion equation (a trivial computer operation) to images of a vineyard collected periodically within season, or perhaps annually over successive seasons. This finding, if borne out by further study, bodes well for operational implementation. Utilisation of SVIs designed for relative insensitivity to changes in soil brightness and atmosphere (Huete 1988, Kaufman and Tanre 1992) may further serve to broaden the spatial, as well as temporal, applicability of remote-sensing technology.

For multi-temporal image analysis, maintenance of internal consistency in spectral values among observation dates will help to suppress sensor-induced changes (noise) in the vegetation index signal. This can be accomplished by converting raw digital counts to physical terms such as at-sensor radiance (as here), based upon laboratory radiometric calibration. Digital counts can also be converted to surface reflectance based upon targets of known brightness within the scene (e.g. Moran et al. 2001, Karpouzli and Malthus 2003). At a minimum, constant gain and exposure settings should be used for all observations, or a strategy should be devised to normalise digital counts for these parameters.

Note also that different sensors can render different NDVI values for identical targets and viewing conditions, based upon radiometric calibration considerations. Vegetation and soils are both generally brighter in the NIR than in the red. Radiometrically calibrated data thus tend to produce NDVIs of range 0 to 1 for agricultural scenes. For these same targets, uncalibrated data can produce NDVI values anywhere within the mathematically possible range (–1 to 1). Even among radiometrically calibrated datasets, apparent NDVI can vary with sensor spectral response function (i.e. band centre and width). For these reasons, the NDVI-LAI equations reported here should be regarded as sensor-specific.

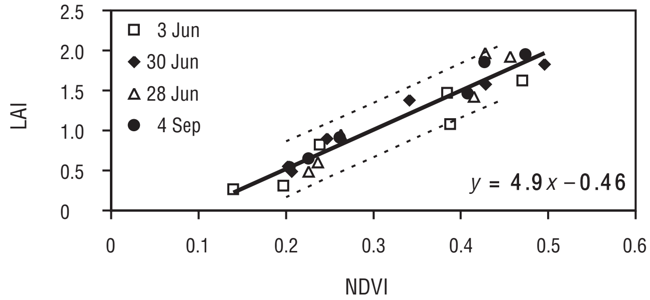

Figure 3. NDVI-LAI relationship for combined data set (6 blocks, 4 time-steps). NDVI observation dates and corresponding symbols are shown in the legend. Corresponding LAI observation dates are given in Table 1. Dashed lines show 95% confidence limits.

Finally, and returning to viticulture, remote sensing can be used to map vineyard canopy density in relative terms through a *radiometric* variable such as NDVI. With additional effort, value can be added to NDVI by transformation to LAI, a *state* variable of agronomic relevance. LAI can then be used to follow vine canopy expansion in quantitative terms, and to provide a physical basis for monitoring shoot balance and water status. For operational implementation, these benefits should be weighed against marginal information costs in the form of fieldwork, image data normalisation, or image processing requirements. Results of this study suggest that the NDVI-LAI relationship is temporally robust, and therefore that the marginal cost associated with supporting fieldwork is warranted. That is, once an initial investment in ground calibration is made, the level of effort required for calibration update may be reduced or even eliminated. To exploit this option, steps should be taken to ensure image data consistency from one time-step to another. Additional study is therefore recommended to confirm a temporal (and spatial) stability between the relationship of remotely sensed SVIs and vineyard LAI as well as for other biophysical attributes on different types of grapevine canopy.

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