Precision Irrigation and Beyond: A Multi-Step Zoning Approach for Vineyard Water Management and Wine Quality Enhancement

Yafit Cohen[1], Idan Bahat[1,2], José M. Grünzweig[2], Victor Alchanatis[1], Ohali'av Keisar[1], Guy Lidor[1], Eitan Goldshtein[1], Yishai Netzer[3,4]

1 Institute of Agricultural and Biosystems Engineering, Agricultural Research Organization, Volcani Institute, Israel
2 The Robert H. Smith Institute of Plant Sciences and Genetics in Agriculture, The Hebrew University of Jerusalem, Israel
3 Department of Agriculture and Oenology, Ariel University, Israel
4 Department of Chemical Engineering, Ariel University, Israel

Abstract

Spatial variability in soil water availability, terrain, canopy development and vine physiology limits the effectiveness of uniform irrigation in vineyards. Precision irrigation can improve the spatial representation of vine water status, but its effectiveness depends on whether local vine response can be modified through irrigation. This paper synthesizes five seasons of work in a commercial Cabernet Sauvignon vineyard in the Judean Hills, Israel, to evaluate when precision irrigation is sufficient and when complementary precision viticulture practices may be required. The analysis combined terrain-based zoning using the topographic wetness index (TWI), UAV thermal and multispectral monitoring, dense field measurements of stem water potential (Ψstem), and micro-vinification of grapes from 20 management cells. Previously published analysis showed that CWSI combined with meteorological variables improved estimation of Ψstem, and that management-cell scale prediction reduced errors relative to uniform whole-vineyard evaluation. The present synthesis further evaluates management-cell responsiveness using the interannual range of wine score and compares responsiveness with TWI and stage III Ψstem. The results indicate that precision irrigation can improve decisions relative to uniform irrigation, but wine-quality response differed strongly among management cells. Responsive and unresponsive cells occurred across the TWI gradient, suggesting that irrigation responsiveness cannot be inferred from terrain-derived water availability alone. Wine-quality modelling indicated that Ψstem near harvest was an important management-related variable, but its effect interacted with terrain, berry traits and seasonal climate. The findings suggest that precision irrigation should be embedded in a broader precision viticulture strategy that also considers canopy regulation, pruning and selective harvesting. The proposed integrated approach is an interpretation arising from the data and requires future field validation.

Keywords: precision viticulture; crop water stress index; topographic wetness index; stem water potential; irrigation management zones; wine quality

1. Introduction

Spatial variability in soil properties, topography and vine physiology is a defining characteristic of many vineyards and a major challenge for efficient water management. Even within relatively small vineyards, differences in soil depth, hydraulic properties, slope and aspect can create substantial variation in water availability, vine growth, fruit composition and wine quality (Deloire et al. 2005; Van Leeuwen and Seguin 2006; Bramley 2010). As a result, irrigation decisions based on a limited number of representative vines or uniform irrigation rates may fail to account for local differences in vine water requirements. This can reduce irrigation efficiency and limit the ability to optimize both yield and wine quality.

Precision irrigation was developed to address this spatial heterogeneity by adjusting irrigation to local conditions. In vineyards, such approaches often rely on delineation of irrigation management zones (IMZs), defined as spatial units that are sufficiently homogeneous in water availability or vine response for a common irrigation decision to be appropriate. Terrain attributes and soil-related variables have been used to delineate these zones because they affect runoff, infiltration and soil water storage. Among these variables, the topographic wetness index (TWI) is particularly relevant because it integrates local slope and upslope contributing area into a spatial indicator of potential water accumulation (Beven and Kirkby 1979; Sørensen et al. 2006). In vineyards, TWI and related terrain indices have been shown to explain spatial variability in vine vigor, water status and fruit composition (Ohana-Levi et al. 2019; Ohana-Levi et al. 2020; Bahat et al. 2021).

However, vineyard water status is not determined by terrain alone. Vine response changes throughout the season as soil water availability interacts with atmospheric demand, canopy development, phenology and management. A location with high potential water availability early in the season may produce a larger canopy and later experience increased transpiration demand. Conversely, low-water-availability zones may differ in the extent to which additional irrigation can alter plant water status. Therefore, both static information, such as TWI, and dynamic information, such as in-season measurements of canopy development and water status, are needed for precision irrigation.

Stem water potential (Ψstem) is commonly used as a sensitive field indicator of grapevine water status and as a basis for irrigation decisions (Choné et al. 2001; Van Leeuwen et al. 2009; Netzer et al. 2019). Nevertheless, Ψstem measurements are laborious, and commercial monitoring is often based on a small number of vines. This limits spatial representation. UAV thermal imagery provides an alternative means of mapping spatial variability in water status. The crop water stress index (CWSI), calculated from canopy temperature, has been widely used for water-stress assessment (Idso et al. 1981; Jackson et al. 1981; Jones 1999; Bellvert et al. 2014). Yet CWSI is affected by image quality, canopy extraction, phenology and meteorological conditions. Therefore, its operational value for precision irrigation depends on whether it can provide Ψstem estimates at a management scale that is sufficiently accurate for irrigation decisions.

Wine quality adds a further layer of complexity. Water status is one of the few terroir-related variables that can be manipulated by management, and moderate water deficit can improve red wine quality (Van Leeuwen et al. 2009; Ohana-Levi et al. 2023). However, climate, terrain, vine vigor, berry traits and management interact non-linearly. Thus, the central question is not only whether precision irrigation provides better estimates or more local decisions than uniform irrigation. It is also whether irrigation alone can bring different vineyard zones toward a desired physiological and wine-quality outcome. This paper addresses that management question by synthesizing five seasons of work in a commercial Cabernet Sauvignon vineyard. The objectives were to: (i) summarize evidence that thermal-based Ψstem estimation can support improved precision irrigation decisions, (ii) evaluate whether management cells differed in wine-quality responsiveness across seasons, (iii) examine whether responsiveness was explained by TWI or stage III Ψstem, and (iv) discuss when complementary precision viticulture practices may be required beyond irrigation.

2. Materials and methods

2.1 Study site and experimental dataset

The study was conducted during 2017-2021 in a commercial 2.4-2.5 ha Vitis vinifera L. cv. Cabernet Sauvignon vineyard located in Mevo Beitar, Israel (31°43′N, 35°06′E), in the Judean Hills wine-growing region. The vineyard was planted in 2011 on 101-14 rootstock, with 1.5 m spacing within rows and 3 m between rows. Vines were trained to a vertical shoot positioned system and irrigated by a drip system. The site is characterized by a Mediterranean climate with cool wet winters and hot dry summers. Elevation ranged from approximately 672 to 702 m above sea level, with a sloped terrain and an elongated wadi crossing the vineyard. The soil is mainly shallow terra-rossa developed over limestone and chalk formations.

The vineyard was divided into 20 management cells (MCs), labelled A-T. Six representative vines were monitored within each MC, giving 120 monitored vines. Measurements collected across the five seasons included Ψstem, leaf area index (LAI), grape composition, irrigation amounts and wine quality. In addition, UAV thermal and multispectral surveys were conducted repeatedly during the season. The multi-year dataset enabled analysis at both the MC scale and broader spatial scales. Detailed descriptions of the site and first two analytical components are available in Bahat et al. (2021) and Bahat et al. (2024).

Wine quality was evaluated by micro-vinification. Grapes harvested from each MC were processed separately, producing small wine batches that were evaluated by professional winemakers. This design allowed the seasonal wine score of each MC to be linked to terrain attributes, irrigation amount and vine water status. The current paper used these data to examine whether interannual variation in wine score could serve as an indicator of management-cell responsiveness.

2.2 Terrain, UAV monitoring and water-status estimation

Terrain-driven water availability was represented by TWI. A digital elevation model generated from RTK-GPS measurements was used to calculate TWI as:

$$\mathrm{TWI} = \ln(A / \tan\beta) \qquad (1)$$

where A is the upslope contributing area and β is the local slope angle. Lower TWI values indicate lower potential for water accumulation, while higher values indicate greater potential wetness. TWI was used in previous analysis to delineate three terrain-based management zones: MZ1, with relatively low TWI values; MZ2, with intermediate values; and MZ3, with higher values closer to the wadi (Bahat et al. 2021).

Thermal imagery was acquired using a UAV-mounted FLIR SC655 thermal camera (FLIR Systems, Billerica, MA, USA), and multispectral imagery was acquired using a MicaSense RedEdge MX camera (MicaSense Inc., Seattle, WA, USA). Thermal images were used to calculate CWSI after canopy-pixel extraction. Multispectral imagery was used to derive normalized difference vegetation index (NDVI) as an indicator of canopy development. Ground Ψstem measurements were collected around solar noon using a pressure chamber after bagging mature leaves before measurement. These measurements served as the benchmark for evaluating remote-sensing-based water-status estimation.

The CWSI-Ψstem relationship was evaluated at five spatial scales in the 2017-2020 dataset: monitored vine, MC, management zone, irrigation block and whole vineyard. Linear models based on CWSI alone were compared with models that also included meteorological variables. Model performance was assessed using the coefficient of determination (R2) and root mean square error (RMSE). The aim was not only to estimate Ψstem but also to evaluate whether management-cell scale water-status maps could support improved irrigation decisions relative to uniform whole-vineyard evaluation (Bahat et al. 2024).

2.3 Precision-irrigation decision evaluation

The irrigation-decision evaluation was based on the retrospective analysis presented by Bahat et al. (2024). In brief, Ψstem predicted from CWSI and meteorological variables was compared with the benchmark Ψstem measured in 120 vines. At the MC scale, predicted Ψstem was used to simulate irrigation decisions for each MC and date. These decisions were compared with decisions based on measured Ψstem. Errors were classified as correct decisions, under-irrigation or over-irrigation. In addition, absolute Ψstem errors from MC-specific prediction were compared with errors obtained by applying a uniform vineyard-scale Ψstem estimate to all MCs. This comparison provided the analytical basis for evaluating whether precision irrigation could improve decisions relative to uniform irrigation.

In the current synthesis, these results were used as the first step of the management argument: precision irrigation can improve representation of vine water status and irrigation decisions. The subsequent analyses addressed the second step: whether improved irrigation decisions are sufficient to control wine-quality response in all cells.

2.4 Responsiveness analysis of management cells

Management-cell responsiveness was evaluated using the interannual range of wine score. For each MC, wine score was available for the five seasons. The range was calculated as the difference between the maximum and minimum wine score observed in 2017-2021. A high range was interpreted as high responsiveness, indicating that the wine-quality outcome of that cell changed substantially among seasons and was therefore potentially more sensitive to environmental conditions and management. A low range was interpreted as low responsiveness, indicating that the cell tended to produce relatively stable wine quality across seasons.

Both the range and the coefficient of variation of wine score were evaluated as indicators of management-cell responsiveness. Because both metrics led to similar interpretations, the range was selected for the main presentation, as it is directly interpretable as the magnitude of wine-quality change observed within each management cell. MCs were classified into responsive, intermediate and unresponsive groups based on the distribution of wine-score range across the 20 MCs. This classification was exploratory and was used to support interpretation rather than to establish a universal threshold.

To examine whether responsiveness could be explained by simple environmental or management variables, the range of wine score was plotted against mean TWI and mean stage III Ψstem. Additional exploratory analyses relating wine-score range to mean irrigation amount and irrigation variability were conducted, but are not presented here because they are beyond the scope of this paper. The purpose of this analysis was to determine whether the observed responsiveness pattern could be attributed to a single factor or whether it suggested more complex interactions among terrain, irrigation and vine physiology.

2.5 Wine-quality modelling and management interpretation

Relationships between wine quality and environmental, terrain and physiological variables were based on the 2017-2021 wine-quality analysis. A support vector regression model and marginal model plots were used to examine the relative importance and response patterns of nine variables, including climate variables, TWI, Ψstem near harvest, berry weight and total soluble solids (TSS). The aim was to identify variables associated with wine score and to evaluate whether a target Ψstem near harvest could be inferred. Because this analysis was observational, management interpretations were treated cautiously. In particular, the importance of Ψstem near harvest was considered a supported result, whereas the need for complementary practices beyond irrigation was treated as an inference arising from the combination of the irrigation-decision results, responsiveness analysis and previously observed canopy-water-status dynamics (Bahat et al., 2026, under review).

3. Results

3.1 Comparison between simulated precision irrigation and uniform irrigation

The first step in evaluating precision irrigation was to determine whether UAV thermal information could provide water-status estimates at a useful spatial scale. The CWSI-Ψstem models improved with increasing spatial scale and with incorporation of meteorological variables. In the CWSI-only models, R2 values increased from 0.36 at the monitored-vine scale to 0.57 at the vineyard scale. After adding meteorological variables, R2 values increased to 0.51 and 0.85 at these two scales, respectively, indicating that meteorological normalization substantially improved model robustness (Bahat et al. 2024).

Despite the higher statistical accuracy obtained at larger scales, operational precision irrigation requires decisions at smaller units. The MC scale provided a useful compromise: accuracy was lower than at the whole-vineyard scale, but spatial representation was much better. When MC-scale Ψstem prediction was used for irrigation decision simulation, decisions were correct for 79.3% of MC-date combinations, with 15.5% under-irrigation and 5.2% over-irrigation errors. More importantly, the MC-specific approach produced lower absolute errors than applying a uniform whole-vineyard estimate to all cells (Fig. 1). Thus, precision irrigation based on spatial Ψstem estimation was expected to improve decision quality relative to uniform irrigation, even if the prediction model was not perfect.

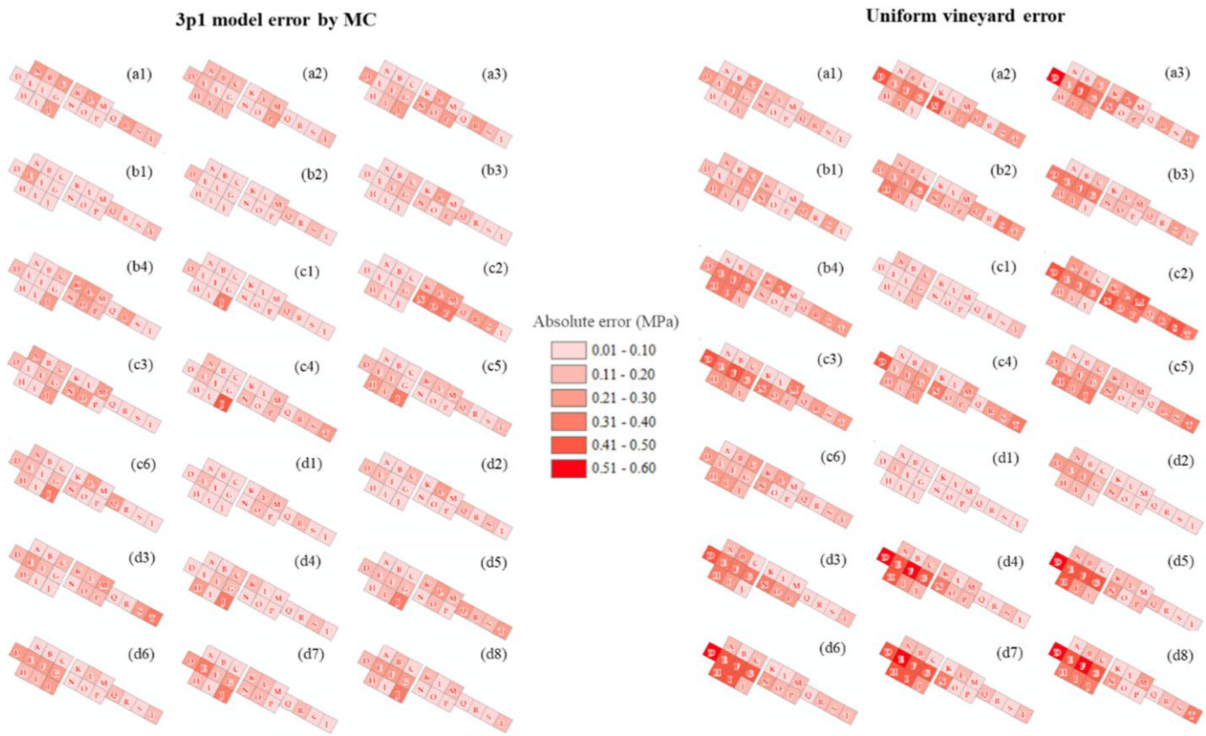

Fig. 1 Absolute error of Ψstem at the management-cell scale using cell-specific prediction model (left) compared with uniform whole-vineyard error (right). Adapted from Bahat et al. (2024)

3.2 Interannual variability in wine quality among management cells

The five-season micro-vinification dataset showed that MCs differed substantially in the interannual range of wine score. Cells A, N, M, J, F, D and P had the largest range and were classified as responsive. Cells E, K, C, H, I, O and Q had the smallest range and were classified as unresponsive. This classification was consistent with earlier visual interpretation based on selected examples, where A and N represented highly variable cells and E and K represented stable cells. However, the full-cell analysis showed that the pattern was not restricted to four selected examples; it was expressed across the vineyard.

The response pattern was not explained by TWI alone (Fig. 2a). Responsive cells occurred at both relatively low and high TWI values. For example, A had low TWI and the largest wine-score range, whereas N had high TWI and also showed high range. Conversely, unresponsive cells were also distributed across the TWI gradient. K and O were unresponsive despite moderate-to-high TWI, while C and E were unresponsive at lower or intermediate TWI values. Therefore, terrain-derived water availability was important for understanding the vineyard context, but it did not provide a simple classification of cells into responsive or unresponsive groups.

Stage III Ψstem also did not provide a complete separation between responsive and unresponsive cells (Fig. 2b). Some responsive cells were located within a moderate mean Ψstem range, but unresponsive and intermediate cells overlapped this same range. Cells with more negative mean stage III Ψstem, such as C and K, had low wine-score ranges, while other cells with less negative Ψstem also differed in responsiveness. These results suggest that mean seasonal water status alone was insufficient to explain wine-quality responsiveness. Rather, responsiveness likely reflected the ability of a cell to translate seasonal conditions and management interventions into meaningful changes in vine physiology and fruit composition.

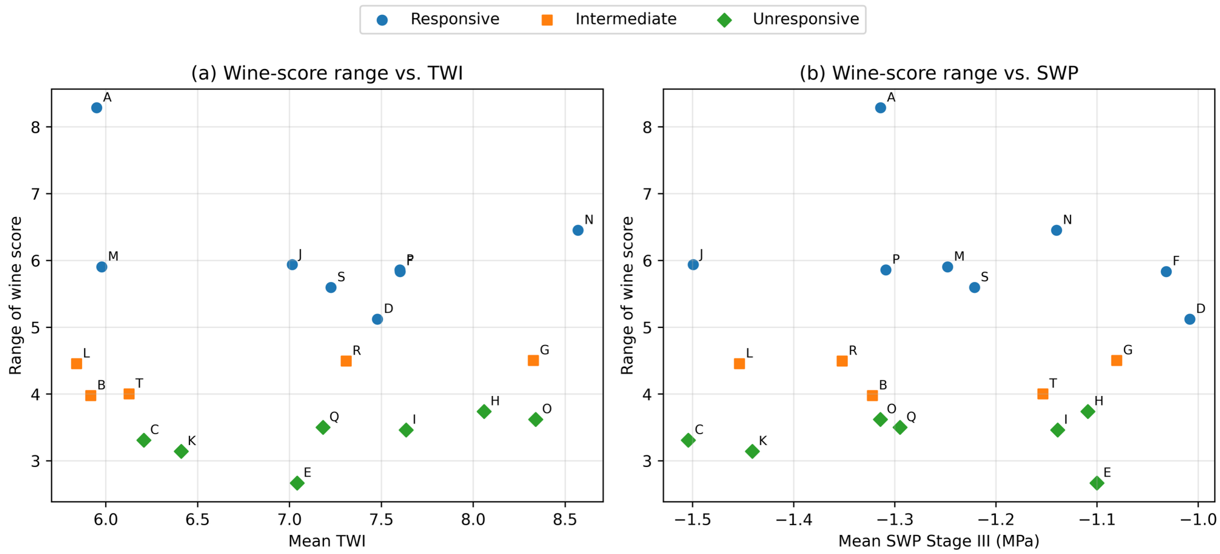

Fig. 2 Interannual range of wine score plotted against (a) mean topographic wetness index (TWI) and (b) mean stage III stem water potential (SWP). Points represent management cells. Responsive, intermediate and unresponsive classes were defined from the distribution of wine-score range across cells

3.3 Relationships between wine-quality range, TWI, and stage III Ψstem

The wine-quality model indicated that climatic variables had the strongest influence on wine score, followed by terrain variables and then physiological variables. Among the physiological variables, Ψstem near harvest and berry weight were important. Marginal response analyses indicated that wine score increased as drought stress increased, reaching a plateau near Ψstem = -1.7 MPa. This suggests that moderate water deficit near harvest was associated with high wine quality in this vineyard.

However, the effect of Ψstem was not independent. Its relationship with wine score depended on TWI, berry weight and TSS, indicating that the same water-status value may not have identical consequences in all cells. These interactions are important for management. They indicate that Ψstem near harvest can be considered a relevant target variable for precision irrigation, but the wine-quality response to that target depends on site-specific conditions and fruit attributes. Therefore, the result supports precision irrigation as a tool for moving vines toward desired water status, but it does not imply that irrigation alone can ensure the desired wine-quality outcome in all cells.

No direct experiment was conducted in which irrigation was independently varied across all cells while all other management factors were held constant. Therefore, the statement that Ψstem is not controlled by irrigation alone is not presented here as a direct causal result. Rather, it is an interpretation supported by three observations: the MC-scale irrigation analysis showed that better spatial decisions are possible; the responsiveness analysis showed that wine-quality range varied among cells even across the same vineyard and similar seasonal irrigation context; and previous terrain-zone analysis showed that canopy development and water availability interacted dynamically during the season. Together, these observations indicate that the management of late-season water status should be interpreted within a broader viticultural context.

3.4 Relationships between wine quality, vine water status, and environmental variables s

The earlier terrain-based analysis provided a physiological explanation for why irrigation alone may not fully determine vine water status. TWI-based zones captured substantial structural differences in the vineyard. MZ1, located farther from the wadi and characterized by lower TWI, had lower vigor, lower LAI, higher drought stress and generally high wine quality. MZ3, closer to the wadi and characterized by higher TWI, had greater early-season water availability and higher LAI. However, by stage III, MZ3 did not maintain a clearly superior water status. Its water deficit became similar to, and sometimes slightly more severe than, that of intermediate zones (Bahat et al. 2021).

This dynamic response suggests that high early-season water availability can increase canopy development and cumulative water consumption, thereby reducing the expected advantage of high water availability later in the season. In other words, the desired Ψstem near harvest may be influenced not only by irrigation scheduling but also by the canopy size that developed earlier in the season. This provides a plausible mechanism for the management conclusion: in some locations, the most effective way to influence late-season water status may not be irrigation alone, but a combination of irrigation and practices that regulate canopy development or fruit exposure.

4. Discussion

4.1 Precision irrigation is useful, but its management domain is limited

The results support precision irrigation as an improvement over uniform irrigation. The MC-scale CWSI- and meteorology-based approach provided better spatial representation of Ψstem and reduced errors relative to uniform vineyard-scale evaluation. This finding is consistent with the basic premise of precision irrigation: in heterogeneous vineyards, local water-status information is needed to avoid over-irrigating some zones and under-irrigating others. It also aligns with previous studies showing benefits of variable-rate or site-specific irrigation in vineyards and other horticultural crops (Sanchez et al. 2017; Ortuani et al. 2019; Ben-Gal et al. 2022).

At the same time, the responsiveness analysis indicated that improved irrigation decisions are not necessarily sufficient to ensure a uniform wine-quality response. Some cells showed large interannual changes in wine score, whereas others remained stable. Importantly, responsive and unresponsive cells were not separated by TWI alone, nor by mean stage III Ψstem alone. This is a critical point for management. A cell may have low water availability and still be either responsive or unresponsive, depending on whether irrigation can meaningfully modify its water status. Similarly, a high-water-availability cell may be unresponsive because natural water availability dominates and little irrigation is applied or needed. Thus, the relevant management unit is not only a zone of different water availability, but also a zone of different response capacity.

4.2 From irrigation management zones to response-based management zones

Traditional IMZ delineation assumes that spatial differences in water availability can be mapped and then managed through differential irrigation. The current synthesis suggests that an additional classification layer is needed. First, structural variability should be mapped using stable variables such as TWI. Second, dynamic water status should be monitored through field measurements and remote sensing. Third, management cells should be evaluated according to their observed responsiveness. Such a hierarchical approach distinguishes between areas where precision irrigation is likely to be effective and areas where other practices may be required.

The distinction between responsive and unresponsive cells should be interpreted cautiously. It was based on five seasons of observations in a single vineyard and on the range of wine score, which integrates climatic, physiological and management effects. It does not prove that a specific cell is inherently responsive or unresponsive under all future conditions. Nevertheless, the classification is useful because it exposes an important limitation of irrigation-only thinking. If a cell remains within a narrow wine-quality range despite seasonal variation and changing irrigation context, then additional management levers may be needed to change its performance. Conversely, if a cell shows a large wine-score range, it may represent an opportunity for management intervention, provided that the driver of variation can be identified.

4.3 Toward integrated precision viticulture

The management implication is that the target water status associated with high wine quality may need to be achieved through a whole-vine approach rather than irrigation alone. The wine-quality model suggested that Ψstem near harvest was a relevant management-related variable and that high wine scores were associated with moderate water deficit. However, the first study in this vineyard showed that canopy development influenced late-season water status, and the responsiveness analysis showed that cells differed in their wine-quality range across seasons. Therefore, a practical precision viticulture strategy should consider not only when and where to irrigate, but also how canopy size, pruning intensity and harvest decisions affect the final physiological and quality outcome.

In zones where high early-season water availability promotes excessive canopy development, precision canopy management or precision pruning may help regulate transpiration demand and improve fruit microclimate. In zones where low soil hydraulic capacity limits the effectiveness of irrigation, increasing water amounts may not be sufficient; canopy regulation, yield adjustment or separate harvest may be more realistic. In zones where desired Ψstem cannot be achieved uniformly before harvest, selective harvesting may help separate fruit with different maturity or quality potential. Similar practices have been proposed in precision viticulture for canopy vigor mapping, pruning and harvest zoning (Campos et al. 2019; Netzer et al. 2022; Priori et al. 2013).

The proposed integrated framework is shown in Fig. 3. It should be viewed as a conceptual framework derived from the observed patterns, not as an experimentally validated decision-support system. The framework begins with management-zone delineation, followed by classification of zones according to responsiveness. Static information such as TWI is then combined with dynamic water-status monitoring and fruit-maturation indicators. The resulting diagnosis guides selection of precision irrigation, canopy management, pruning or selective harvesting. Future validation would require complex multi-year experiments comparing irrigation-only strategies with integrated precision viticulture treatments across sites, cultivars and climatic conditions.

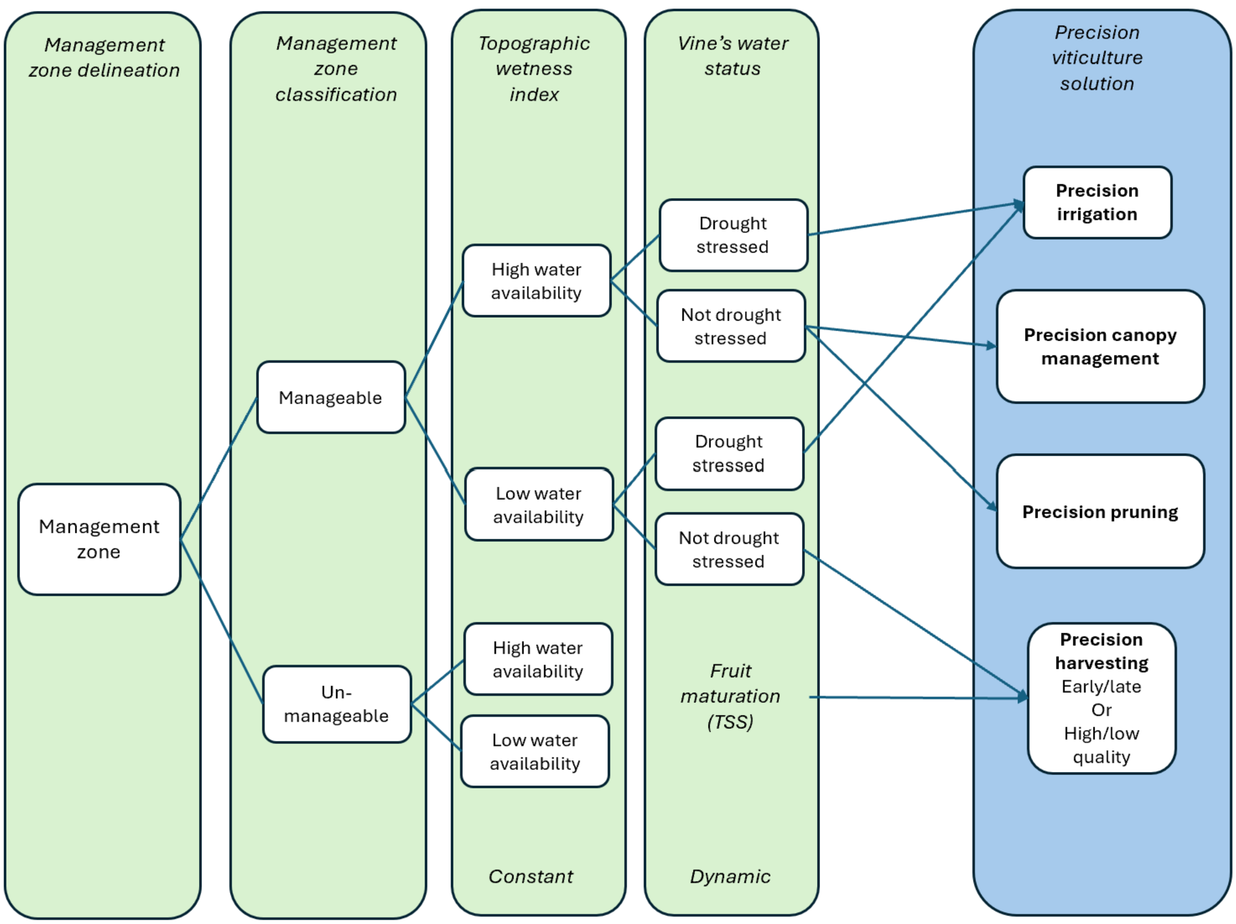

Fig. 3 Conceptual framework for integrated precision viticulture. Management zones are first delineated and then classified according to responsiveness. Static terrain information and dynamic water-status or fruit-maturation indicators are combined to guide precision irrigation and complementary practices such as canopy management, pruning and selective harvesting

4.4 Limitations and future work

Several limitations should be acknowledged. First, the responsiveness analysis used wine-score range across five seasons as an exploratory indicator. This metric is intuitive and management-relevant, but it is sensitive to the number of seasons and to the scoring scale. Second, irrigation amounts were not manipulated in a fully factorial experimental design across all MCs. Therefore, causal effects of irrigation, canopy and terrain cannot be fully separated. Third, the proposed integration of pruning, canopy management and selective harvesting was not tested experimentally in this study. The framework should therefore be considered a hypothesis-generating outcome that can guide future experiments rather than a proven prescription.

Future work should test whether response-based classification improves management decisions relative to TWI-based zoning alone. Such experiments would need to combine spatially variable irrigation with spatially variable canopy or pruning treatments, while preserving the ability to evaluate wine quality by management cell. Although such experiments are logistically demanding, they are needed to determine whether integrated precision viticulture can reliably increase wine quality, improve water-use efficiency and reduce spatial variability within premium vineyards.

5. Conclusions

Precision irrigation based on spatial Ψstem estimation was shown to improve water-status representation and irrigation-decision quality relative to uniform vineyard-scale evaluation. UAV-derived CWSI combined with meteorological variables provided a useful basis for mapping Ψstem at the management-cell scale.

However, improved irrigation decisions did not imply that all vineyard cells could be managed toward the same wine-quality outcome by irrigation alone. Interannual wine-score range differed among management cells, and responsive and unresponsive cells occurred across the TWI gradient. Thus, TWI is an important layer for understanding vineyard structure, but it does not by itself explain management responsiveness.

Wine-quality modelling indicated that Ψstem near harvest was a relevant management-related variable, with high wine scores associated with moderate water deficit. Yet the effect of Ψstem interacted with terrain, berry traits and climate. Together with evidence that canopy development can modify late-season water status, these findings suggest that precision irrigation should be embedded within a broader precision viticulture strategy. Complementary practices such as canopy management, precision pruning and selective harvesting may be required where irrigation alone cannot modify vine response sufficiently. This conclusion remains a management interpretation that should be tested in future multi-year field experiments.

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