EVALUATION OF A COMMERCIAL GRAPE YIELD MONITOR FOR USE MID-SEASON AND AT-HARVEST

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Abstract

Aims : Yield monitors are becoming more common in North America. This research evaluates the precision and accuracy of a retro-fitted, commercially available grape yield monitor mid-season, for crop estimation and crop thinning applications, and at harvest for yield mapping.

Methods and Results : Several grape yield monitors were mounted on the discharge conveyor belt of grape harvesters in both commercial and research vineyards in North America. Sensor response was compared to manual measurements at multiple masses, ranging from 20 kg to 28 Mg over the course of three seasons. Measurements were taken during crop thinning and estimation (mid-season) and at harvest. Results showed that the grape yield monitor performance was sufficient to generate good spatial maps of the relative variation in harvest yield and mid-season thinned yield. However, at harvest the sensor showed a shift in response between days of up to ±15 %, such that the generation of absolute yield maps required a daily calibration against a known mass. Within a day (single harvest operation) the sensor response did not appear to drift. Mid-season applications required a different calibration to harvest applications.

Conclusion : The yield sensor worked well for both mid-season and at harvest operations in North American vineyards but required a daily calibration to avoid drift issues. The mid-season yield calibrations were different between seasons ; however, the harvest calibration factor was stable between seasons.

Significance and Impact of study : The study showed that a commercial yield monitor with correct calibration was effective at even low fruit flow. This opens the possibility of using a harvest sensor mid-season to mechanically estimate fruit load from small point samples and to map the amount of fruit removed during fruit thinning operations. This will improve the quality of information available to viticulturist to understand fruit and crop load. The commercial yield monitor is suitable for use in North American vineyards.

Keywords : on-the-go proximal sensing, yield mapping, crop estimation.

Résumé

Objectifs : Les capteurs de rendement deviennent de plus en plus communs en Amérique du nord. Cette étude vise à évaluer la précision et l'exactitude d'un capteur de rendement viticole disponible dans le commerce, étalonné avec des valeurs réelles. Il est utilisable à mi-saison pour estimer la récolte et durant les vendanges pour cartographier le rendement.

Méthodes et résultats : Plusieurs capteurs de rendement viticole ont été montés sur le convoyeur de décharge de machines à vendanger, à la fois au sein de vignobles commerciaux et de recherche en Amérique du nord. La réponse du capteur a été comparée à des mesures manuelles pour plusieurs masses, allant de 20 kg à 28 Mg au cours de trois saisons. Les mesures ont été réalisées au cours de l'éclaircissage et de la prédiction de récolte (à mi-saison) et durant les vendanges. Les résultats ont montré que la performance du capteur de rendement viticole était suffisante pour cartographier de manière fidèle la variation relative du rendement à la récolte et celui de l'éclaircissage à mi-saison. Cependant lors des vendanges, le capteur a montré un décalage dans sa réponse selon les jours, allant jusqu'à 15 %. Au sein d'une journée (pour une vendange unique), la réponse du capteur ne semble pas dériver. L'utilisation à mi-saison exige un étalonnage différent de celui pour les vendanges.

Conclusion : Le capteur de rendement fonctionne bien dans les vignobles d'Amérique du nord mais demande un étalonnage quotidien afin d'éviter des problèmes de dérive. Les étalonnages de mi-saison et de récolte sont différents, bien que le facteur d'étalonnage durant les vendanges a été stable au fil des saisons.

Signification et impact de l'étude : L'étude a montré qu'un capteur de rendement disponible dans le commerce avec un étalonnage correct a été efficace, même pour un faible flux de raisins. Cela ouvre les possibilités d'utiliser un capteur de rendement à mi-saison afin d'estimer mécaniquement la charge en fruit et de cartographier les fruits enlevés lors de l'éclaircissage. Cela permettra d'améliorer la qualité de l'information disponible pour les viticulteurs afin de comprendre et interpréter la charge en fruit et la production potentielle.

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INTRODUCTION

On-harvester grape yield monitors have been commercially available since the late 1990s. The first commercially available grape yield monitor was the HM-570 grape yield monitor released by HarvestMaster (Logan, UT, USA). The HM-570 was a volumetric sensor that used ultra-sonic sensors mounted above the discharge conveyor to measure the height (volume) of grapes on the conveyor belt. Volume was then calibrated to mass using a density coefficient. Considerable issues with the operation of the system in Australian conditions between 1999 and 2002 were noted by researchers at CSIRO and The University of Sydney (Taylor, 2004). In particular, the density coefficient required constant adjustment, not only between varieties but also throughout the day as the ratio of berries to must being offloaded changed.

In 2001, Farmscan Ltd (Western Australia, Australia) released a load cell-based grape yield sensor that proved to be more reliable than the HarvestMaster system (Taylor 2004) ; however problems with Farmscan's parent company effectively resulted in the Farmscan grape yield sensor being withdrawn from the market by 2007. A second load cell-based system was commercially released in 2005 in Australia by Advanced Technology Viticulture (ATV) (Adelaide, South Australia, Australia) Since 2005 there has been a slow but steady increase in adoption of the ATV grape yield monitor, predominantly in Australia but increasingly in North America with 6 yield monitor installations in the USA in 2012, 9 in 2013 and >30 in 2014.

Examples of yield maps have been presented in the literature (Bramley & Hamilton, 2004 ; Tisseyre et al., 2007 ; Arnó et al., 2009), as well as a geostatistical analysis of the spatial variation observed in Australian and European viticulture (Taylor et al., 2005) ; however, there has been no independent evaluation of this technology published. Given the increased interest in grape yield monitors in the USA, and the expected continued growth in adoption, an evaluation of the accuracy and the potential uses of this technology is considered pertinent.

MATERIALS AND METHODS

1. System and Installation

The only currently available commercial grape yield monitor is manufactured, installed and supported by Advanced Technology Viticulture (ATV). The ATV grape yield monitor (GYM) is designed to be retrofitted to a discharge conveyor belt and can be altered to fit most makes of grape harvesters that use a discharge conveyor. The yield sensor consists of a weigh-frame on load cells under the discharge conveyor belt of the harvester that weighs the grapes as they are being off-loaded. A belt speed sensor, a junction box and a data logger/controller in the tractor cabin complete the system. For mapping capabilities a Global Navigation Satellite System (GNSS) receiver is also required. After each installation, a static calibration of the load cells is performed by placing known dead weights on the discharge conveyor belt over the sensor. This is to ensure that the system is operating within acceptable limits and has been correctly installed. A daily, dynamic calibration (rezeroing) of the system should be performed prior to operation to tare the force being exerted on the load cells by the empty belt. In total, 7 GYM systems were used within this study : 5 systems were installed on commercial harvesters that operated primarily in winegrape vineyards in the San Joachin valley in California, 1 GYM system was installed on a commercial harvester in the Lake Erie region, NY State and 1 GYM system was installed on a harvester associated with the Cornell Lake Erie Research and Extension Laboraty (CLEREL) juicegrape vineyards in the Lake Erie viticulture area in NY State.

2. Evaluation

The GYM was designed for use at harvest. The accuracy and precision of the GYM systems at harvest was assessed by comparing sensor measurements against recorded masses of bin loads (0.1 – 0.7 Mg) and truck loads (5 – 30 Mg) in both California and New York. In addition to harvest assessment, the GYM was evaluated for use mid-season during fruit load estimations (5 – 70 kg) in New York. Mid-season use is a novel application of this technology in this study. It has two potential applications 1) as a means of automated crop estimation in production systems, such as juicegrape systems, where destructive sampling for crop estimation is common, and 2) for mapping fruit load removal when crop-thinning is employed as a mid-season management tool.

Truck scale measurement at harvest : For the 2012, 2013 and 2014 harvests, the daily mass of grapes sensed was compared to the mass of grapes delivered to the crush. In 2012, these data were only from the CLEREL GYM (n 11). In 2013, additional data from sensors on 5 different commercial harvesters in California were available (n 31), as well as the CLEREL harvester (n 12). In 2014, data were only obtained from the CLEREL harvester (n 13). All these data were collected at the truck-load scale, with the CLEREL data varying from small flat-bed trucks (~5 Mg) to full semi-trailer loads (~25 Mg). The commercial data in each year were only available as full semi-trailer load measurements (20-25 Mg). Data were collected over a period of several weeks in each year, though not always daily. All the GYM sensors were calibrated, but the data were not corrected to adjust the daily total GYM mass to the delivered crush mass. Each measurement was therefore affected by the quality of GYM operation (re-zeroing and maintenance) and the nuances of the harvester operation. The daily error (as a percentage) was calculated for each truck load; however, to compare across production systems and harvesters, only error data associated with full semi-trailer loads is presented (n 51).

Bin scale measurements at harvest: In both 2012 and 2013, the CLEREL GYM was used to harvest half-row trials (16 rows - 32 trials with 45 vines/trial) at the CLEREL vineyard, Portland, NY. Each trial was individually harvested and weighted on a Cardinal 708 floor scale (2268 kg ±0.45 kg) (Cardinal Scale Manufacturing Co., Webb City, Missouri, USA) so that a comparison between the scale mass and the GYM-sensed mass could be made. Fruit load per trial varied but was typically about 400 kg (approximately half a harvest bin). In both years, all data were collected on the same day and the total daily mass sensed was adjusted to the total delivered (crush) mass. This trial was not run in 2014.

Bucket-scale measurements mid-season for crop estimation: In 2013 and 2014 the yield monitor was evaluated for use mid-season (July) during yield estimation. In July 2013, measurements (n 57) were taken over two days on the CLEREL vineyards from areas as small as a single panel (typically 7.32 m containing 3 vines) to multiple panel lengths using the CLEREL harvester and GYM. In July 2014, data were obtained from two GYMs in the Lake Erie viticulture area; the CLEREL harvester (n 15) and a GYM on a commercially operated harvester (n 69). The CLEREL harvester obtained data from two-panel sections, whilst the commercial operator used a fixed distance (14.6 m) to avoid issues with irregularly spaced panels in the vineyards. In all cases, the GYMs were operated mid-season with the harvest calibration factors. For each sampling site the harvested fruit was captured off the end of the discharge conveyor into a bucket and weighed using either an Ohaus D-5-MO platform scale (20 kg capacity) (Nänikon, Switzerland) or a hand-held spring scale (25 kg capacity) (INS-T, Chatillon, NY, USA). Where yield was > 20 kg, the captured berries were sub-divided and multiple weights taken. The GYM readings were captured by the GNSS-enabled data logger. Post-processing was performed to extract the GYM recorded mass at each point and relate it to the manual scale measurements. For plotting and analysis, these data were not corrected against the total mass of grapes harvested at this time.

The intent here is to provide information on the precision and accuracy of the GYM against actual mass at different scales. Only the harvest truck load (crush) data had a temporal dimension, with data collected on multiple days over several weeks in each year. The other data were collected on either one single day or over short time periods (2-4 days).

For all three approaches, plots of the GYM vs actual scale mass were generated. Linear regression was performed with the intercept constrained to (0,0). The coefficient of variation (R^2) and root mean square error (RMSE) were calculated. The histogram of the percentage errors (%E = [(Actual-Sensor)/Actual]*100) for all the truck measurements from both the research (CLEREL) and commercial GYMs were also calculated. For the truck-scale data, linear regression fits were performed separately for the CLEREL and commercial data sets due to the difference in range of values (truck loads). All analysis was performed in JMP Pro v11.1 (SAS Institute, Cary, NC, USA).

RESULTS

Truck-scale measurements: Figure 1 shows the relationship between the GYM readings and the mass of weighed grapes for truck-scale data collected at harvest in both California and NY State. The CLEREL truck data had a large range of values (4.5–23.6 Mg) and a strong fit (R^2 0.95) (Fig 1a). The RMSE was 1.43 Mg or 7.87 % of the mean (18.18 Mg) response. The fit was stable over the three years of the study at CLEREL. The commercial data from California had a much lower range (21.6–28.1 Mg) as it was restricted to full semi-trailer loads, and had a lower fit for the regression (R^2 0.4). This is probably due in part to the shorten range (relative to the CLEREL data) and the fact that the data was derived from 5 different GYMs (harvesters) across multiple sites and states compared to a single GYM at CLEREL. Even with the lower fit, the gradient is very similar between the two sets of data, and very close to a 1:1 fit. This is indicative of well calibrated sensors. The RMSE error from the commercial data set was 1.75 mg, which is higher than the CLEREL data set. The mean response was

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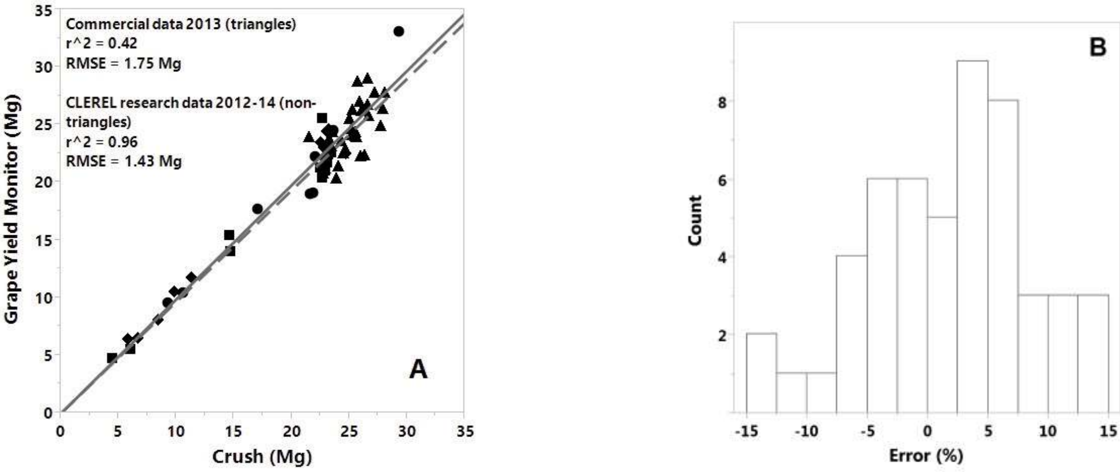

Figure 1. A) Plot of the actual vs. sensed mass of grapes at truck-load scale (squares 2012 CLEREL ; circles 2013 CLEREL ; diamonds 2014 CLEREL ; triangles 2013 commercial data).
Dashed line is fit of a linear regression to the CLEREL data (2012-14).
Solid line is the fit of a linear regression to the 2013 commercial data. R^2 and RMSE values for the linear regressions are provided on the plot. B) A histogram of the daily errors associated with 51 individual full semi-trailer measurements.

also higher (24.63 Mg), such that the RMSE was 7.11 %, or similar to the CLEREL data set. The % Error distributions are shown in Fig. 1b for all the data combined (CLEREL and commercial). There was a slight bias, with the GYM reading lower than the crush (truck mass) on average (~2.5 %). The % Errors were in the range of ±15 % of truck weight and were independent of the truck load size or the year or the type of harvester for this data set (data not shown).

Bin-scale measurements : The precision of the GYM on any given day at harvest was assessed from the plot trial data (Fig. 2). The yield data were corrected against the delivered crush mass in each year (to correct for the daily error observed in Fig. 1). The corrections were respectively -5.13 % and -3.35 % for 2012 and 2013. The yield in 2012 was lower than in 2013. The mass of harvested fruit per trial ranged from 89 to 816 kg over the two years. As expected with the correction, the linear regression follows a 1:1 fit across the two years, and the fit is very strong with R^2 0.95 and RMSE 35 kg (or 9.70 % of the mean response). There was no indication that there was any shift in the quality (error) of the sensor response over the course of the day when plots were harvested (data not shown).

Mid-season measurements : Figure 3 shows uncorrected fits of GYM-sensed vs actual mass from very low masses of grapes picked mid-season during crop estimation practices in the Lake Erie juicegrape viticulture region. There were three datasets – two from CLEREL (2013 and 2014) and one from a commercial grower (2014). The range of harvested grapes was 1.3 to 97 kg across all data. In Fig. 3 the three data sets are fitted separately and show very different gradients ; however all three show a reasonable to strong fit for field-collected data with outliers removed (R^2 0.70-0.92). The 2013 and 2014 mid-season CLEREL regression fits had different gradients between years, which contrasts with the stability of the inter-annual harvest regression fit (Fig. 1a). The difference in gradient between years is probably associated with yield estimations at different stages of berry development. The CLEREL 2014 mid-season data had the fewest points (n 15) and the worst fit (R^2 0.29). The CLEREL 2014 data had three points that were outliers (shown as open circles in Fig. 3). These points were probably associated with harvester problems, particularly problems associated with belt operations. These issues were identified at the time but were not logged against individual data points. The linear fit shown in Fig. 3 was generated without these outlying points (open circles) and the fit improved considerably (R^2 0.73, n 12). This highlights the need for care in both manual measurements and machine operation during crop estimation. The commercial 2014 mid-season data were collected by a grower under commercial operating conditions, i.e. not with the rigour of the CLEREL research-oriented measurements. There were some points omitted due to untidy record keeping, however these data still had a strong linear relationship between the GYM and scale measurements (R^2 0.70).

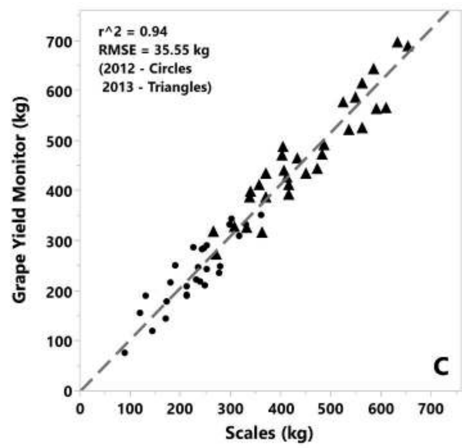

Figure 2. Plot of the actual vs. sensed mass of grapes at the partial bin-load scale from half-row experiments in a Concord (*Vitis labrusca*) vineyard at CLEREL vineyard (circles 2012 and triangles 2013).
The linear regression was fit across all data.
The R^2 and RMSE values are provided on the plot.

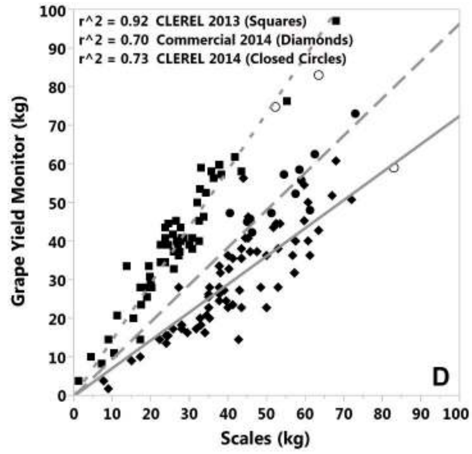

Figure 3. Plot of the actual vs. sensed mass of Concord juicegrapes at a bucket-scale (squares 2013 CLEREL ; circles 2014 CLEREL ; diamonds 2014 commercial vineyard data).
The sensor calibration coefficient was held constant, which resulted in different dates having different gradients for the linear fits. The open circles were data from CLEREL 2014 that were assumed to be erroneous and not used for the linear regression fits.

DISCUSSION

Assessment of the yield monitor at multiple scales of mass measurement showed that the sensing system provides good information across all scales. The yield monitor is subject to some temporal shift that can create absolute errors of ±15 % in measurement between days at harvest. Consequently, for optimum results at harvest, the daily sensor total should be adjusted against the total mass of grapes weighted at the crush. In single harvester systems this is relatively straight forward ; however, when multiple harvesters (sensors) are used in a vineyard it can be more difficult to track weights back to a single machine. Unfortunately, proper correction is also more important in multi-sensor vineyards, as different machines are likely to have different errors on a given day. The importance of this daily correction will depend on how the information is used and whether relative information on high and low yielding areas or absolute information is needed by the producer. This is a potential limitation to adoption of the GYM in larger, multi-harvester vineyards.

Daily calibrations are even more important for any mid-season applications of the GYM. These data indicate that for mid-season use of the GYM a different calibration coefficient is needed to that used at harvest, and it appears that this coefficient is dynamic as the berries develop. It is hypothesised that sensor performance is affected by differences in berry physiology, with lighter, smaller, harder berries mid-season compared to large juicy grapes at harvest, and the absence of the must (juice) weight. Further studies are needed to test this hypothesis. However, the linear fits observed in this evaluation indicate that recalibration should be relatively simple and will produce sensible results. The CLEREL 2013 and 2014 mid-season data indicate that the calibration is likely to be year-specific, despite the harvest calibration being stable between years. Again the reason for this is not known, but if the calibration is affected by berry physiology, then the rapid growth and change in berry development during this period is likely to generate a dynamic calibration coefficient until berry size and mass stabilise. It may be possible to have a generic calibration if crop estimation can be timed for the exact same stage of berry development each year, but this is considered difficult to achieve in commercial enterprises.

This is the first reported use of the GYM mid-season and the quality of the results in Fig 3 show great promise for the application of the GYM for 1) crop load estimation from destructive harvesting mid-season and 2) mapping removed fruit during thinning operations. The former has the potential to revolutionise yield estimation in viticultural systems where destructive sampling is common, while the latter will allow precision viticulture to be better applied to crop load management. Future studies are needed to further quantify these potential applications, especially in commercial systems.

The stability and linearity of the response for a given day, either mid-season or at harvest, is indicative of a system that is suitable for pattern identification

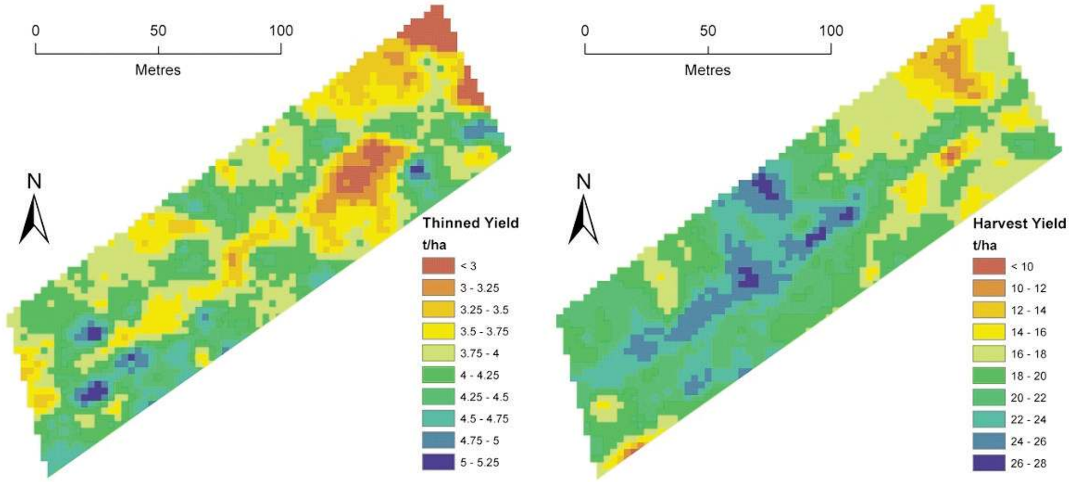

Figure 4. Example of the spatial patterns associated with grape yield monitoring during crop thinning mid-season (left) and at harvest (right) at the CLEREL Concord juicegrape vineyard, Portland, NY.
All data collected with a GNSS-enable grape yield monitor. Thinned yield data (left) has been post-processed to correct for mid-season bias in operation. Note the difference in spatial patterns between the two maps.

regardless of the quality of the sensor calibration. That is, even though the data may contain some absolute error, the relative patterns generated by these yield data are correct. An example of the observed spatial patterns in a mid-season crop thinning map and a final (harvest) yield map are shown in Fig 4. The difference in mass removed is evident (median values of 4 and 18 Mg/ha for the thinned and harvest yield respectively) even when considering that at this mid-season stage the berry weight is approximately half that of berry weight at harvest. Broad, coherent patterns (patches) are evident in both maps, although there are different patterns in the midseason and harvest maps. The reasons for this are not clear at the moment, but are of obvious interest for viticulturists looking to manage fruit load.

It is important to understand that these spatial grape yield data are different to spatial yield data from other crops, particularly combinable arable crops. Principally this is because grape harvesters are very efficient at removing and offloading the berries and there is very little convolution or mixing of the berries within the harvester. This is in contrast to the level of convolution and resultant data smoothing that occurs in combine harvesters (Whelan and McBratney, 2002). The efficiency of the grape harvester means that a lot of the short-range and stochastic variation in production is transferred to the yield sensor. Visually this makes a 'noiser' point raw yield and correct interpolation is needed to better visualise, analyse and interpret the spatial patterns in yield (Bramley & Williams, 2001 ; Bramley 2005 ; Bramley et al., 2008).

CONCLUSIONS

The evaluation of the sensor response against manual measurements showed a strong linear relationship during use mid-season and at-harvest. The sensor response was stable and linear within a harvesting operation ; however, between days (operations) there was often a shift in the sensor response that could lead to an absolute error of ±15 %. The grape yield monitor was determined to be effective for visualizing relative spatial yield patterns, but the yield data requires a daily adjustment (re-calibration) against a measured mass if these relative patterns are to reflect absolute yield variations. Evaluation of the GYM mid-season showed that it was suitable for use at this stage with possible applications in crop estimation and mapping of crop thinning.

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