EFFECT OF A VARIABLE RATE IRRIGATION STRATEGY ON THE VARIABILITY OF CROP PRODUCTION IN WINE GRAPES IN CALIFORNIA

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ABSTRACT

Pruning and irrigation are the cultural practices with the highest potential impact on yield and quality in wine grapes. In particular, irrigation start date, rates and frequency can be synchronized with crop development stages to control canopy growth and, in turn, positively influence light microclimate, berry size and fruit quality. In addition, canopy management practices can be implemented in vineyards with large canopies to ensure fruit zone microclimate is optimized for producing high quality fruit.

Spatial variability in soil properties such as water holding capacity causes variability in fruit yield and quality. Ideally, irrigation should be applied differentially throughout the vineyard in order to compensate for soil variation and optimize both fruit yield and quality. We report on the first-season effect of a variable rate irrigation (VRI) prototype on canopy development and yield. The prototype system was implemented in early 2013 in a 4.05-hectare quadrant inside a drip-irrigated mature Cabernet Sauvignon vineyard measuring 12.5 total hectares. The VRI quadrant contained the full range of lowest to highest yields present in the vineyard (14.4 to 28.1 tons/ha), based on the 2012 yield map. The VRI quadrant was split into one hundred and forty 15 x 15-meter irrigation zones which were watered independently by drip irrigation with weekly schedules calculated using an energy balance approach based on the Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) model. The 2012 yield map was used to split all irrigation zones among low, medium and high yield classes. Irrigation during the 2013 growing season was

initiated in both the low and medium 2012 yield classes at a time when the soil was still saturated (i.e. earlier than standard practice), while watering in the high 2012 yield class was withheld until vines had used a significant amount of the soil water holding capacity (i.e. standard practice). Low yielding zones received up to 17% more irrigation water than the high yielding ones during the 2013 growing season. For both 2012 and 2013, normalized difference vegetation index (NDVI) was calculated and mapped from airborne images captured in mid-August and yield was mapped from yield monitor data collected at harvest.
VRI affected spatial and non-spatial vineyard variability parameters. Non-spatial variability of both yield and NDVI, measured either as percent coefficient of variation or as percent spread (the range as percent of the median), decreased significantly from 2012 to 2013 in the VRI section compared with an adjacent 4.05-hectare section of conventionally irrigated vineyard. Compared to conventional irrigation (CI), VRI also decreased spatial dependency and structure as indicated by the mean correlation distance (MCD) and the Cambardella index (CmbI). This is the first of three seasons planned for the testing of this system that includes many soil, vine, fruit and wine attributes.

Keywords: precision irrigation, variable rate irrigation, wine grapes, *Vitis vinifera* L., yield map

INTRODUCTION

During no other time in history has drought been more critical to California's agriculture than now. Both the state's urban population and agricultural planted acres have grown to critical size, demanding more water than ever. At the same time, environmental regulations, limited number of reservoirs, reduced water deliveries, higher prices per acre foot, and a steadily depleting state aquifer are testing overall economic margins for growers and crop production sustainability, including wine grapes. Compared to other permanent crops such as citrus and almonds, wine grapes use much less water per season. However, vineyard development and production costs are much higher resulting in potentially lower grower profits. More efficient irrigation system design and novel irrigation practices are needed in wine grape production in order to stretch available water resources.

Background

Traditional vineyard management is based on the application of uniform practices across the vineyard, with every vine receiving the same rate or input measure, including irrigation water. But vines do not behave uniformly throughout the vineyard; due to differences in soil properties and topography, differences of up to 10-fold are common in vine yield from high to low spots (Bramley and Lamb 2003). Similar differences exist in canopy surface and density, resulting in some areas of the vineyard demanding and transpiring more water than others. Ideally, vineyards would be divided into distinct zones and differentially irrigated according to canopy size. Unfortunately, irrigation technology has not yet developed a differential irrigation system for vineyards or for any other permanent crop. Approaches to differential irrigation have been implemented as sensor-triggered systems in greenhouses (Lichtenberg, Majsztrik, and Saavoss 2013), small farms (Kamel et al. 2012) or in center pivot-irrigated grain crops (Patil and Al-Gaadi 2012). Based on classification procedures of canopy reflectance data alone or in combination with yield, high density soil data, or leaf water potential, vineyards have been divided in a small number of management zones and irrigated accordingly in Australia (McClymont et al. 2012; Proffitt and Pearce 2004) and Spain (Bellvert et al. 2012; Martínez-Casasnovas, Vallés Bigorda, and Ramos 2009). The work in Australia resulted in a reduction of variability in vegetative growth and yield whereas in Spain there were no reductions in yield variability. In some drip-irrigated California vineyards variable watering rates are empirically achieved by increasing or decreasing the number of emitters per vine. However, the variable rates achieved are hard to modify independently and the length of irrigations cannot be controlled because all the emitters are connected to the same circuit and one pump.

The main objective of the study described herein is to develop and operate a proof-of-concept VRI system prototype and validate it by decreasing vineyard variability, increasing fruit yield and quality, and therefore increase water use efficiency. The system was conceived, designed and installed in the field in early 2013 and operated for the entire 2013 season. In this preliminary report, we present the basic design and functioning principles of the system as well as its effect on vine yield and canopy development variability and water use efficiency on its first year of operation.

MATERIALS AND METHODS

Vineyard and experiment layout

One highly variable, hand-pruned, drip-irrigated, 17-year old Cabernet Sauvignon vineyard, for which yield had previously been mapped during the 2012 harvest, was selected for this study. The 12.95-ha block is located south of Wilton, California (38°21'13.60"N/ 121°15'1.80"W; elevation 21 meters) with the vines planted at 3.35 m by 1.52 m, on east-west oriented rows on two predominant soil types (USDA-NRCS SSURGO database): San Joaquin silt loam (213), leveled (~ 75%) and San Joaquin-Galt complex (217), leveled (~ 25%). The vines are grafted on Teleki 5C rootstock and trained to horizontally-split canopies with double cordons running unilaterally. Local average precipitation amounts to 500 mm annually with maximum rainfall occurring during January. Vineyard floor management includes maintenance of a bare soil strip in the vine rows and a rye grass mixture between vine rows which senesces around mid to late spring, depending on rainfall. Standard cultural practices for the region and variety are carried out at the discretion of the vineyard manager.

The VRI study was set up in a 4.05-ha rectangular area of the block that included the full range of yields seen in the rest of the block based on the 2012 yield map (Figure 1). Areas of similar high and low yields were also secured in the remainder of the field, watered with CI. The perimeter of the VRI experiment was aligned with the 30 x 30 m pixels of the Landsat image outputs. Each pixel outline was further divided into four 15 x 15 m quadrants, each one defining the outline of an independent irrigation zone. This delineation resulted in a rectangle containing 140 irrigation zones, 10 zones running east to west, by 14 zones running north to south. Because the row distance is not an exact multiple of irrigation zone size, the number of rows per zone alternates from four to five in the north to south direction. All zones have 10 vines in the (E-W) row direction, for a total of 40 or 50 vines per zone. The VRI study occupies a total of 63 rows, each 190 m long.

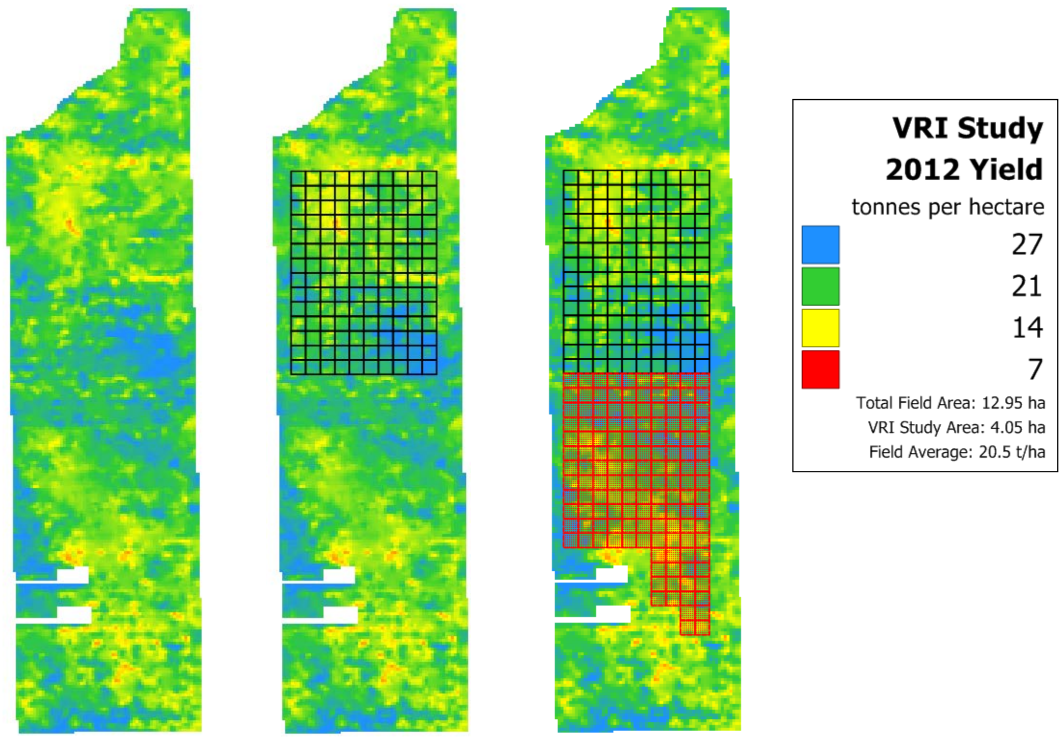

Fig. 1. Layout of the variable rate irrigation study (black grid) and an equal area on CI (red grid) for comparison of data. There are 140 (15 x 15 m) zones in each grid. The background vineyard fill is the 2012 yield map.

Irrigation system design

The VRI system prototype consists of a variable flow submersible pump, underground pipes of different sizes running from the well to the middle (east) side of the experiment, main and submain water valves, flow meters, and a large vertical wooden panel holding several enclosures for power and electronics components as well as the central computer, an antenna and wireless modem for remote access and control of the system. Two plastic irrigation hoses (1.78 cm outside diameter) run parallel to each other 15 cm apart on a vertical plane. The upper hose is fastened to a wire running along the vine row at a height of 60 cm. The lower hose runs along with the primary irrigation system hose and both are held by a second wire at a height of 45 cm. The two wires are fastened to the vine support stakes and both hoses are connected to each other through an "H" PVC assembly, in place every 33.5 m, the distance corresponding to the 10 vine spaces corresponding to each irrigation zone. Only the lower hose has emitters, two per vine. Independent irrigation of the each of the four or five 10-vine sections of each zone is achieved by a solenoid valve, a check valve, a waterproof enclosure containing an electronic control board as well as power and communication wiring. There are additional solenoid valves at the beginning of each gateway and at the end of each row for system flushing for a grand total of 707 valves. Irrigation and communication wiring run together along the vine rows, fastened to the upper wire. The primary irrigation system has been kept in place as backup and for application of liquid fertilizers when needed.

Irrigation of the 140 zones is controlled by a computer network with a single master coordinating operation (Figure 2). The master and individual control nodes communicate using master-slave messaging protocol based on MODBUS (Modbus.org 2006). A read/write memory abstraction is used to issue commands to control nodes and retrieve information from attached sensors. Combined with the RS-485 (Soltero et al. 2010) physical and electrical signaling layer MODBUS can achieve a moderately high speed transmission rate over the up to 1000-meter cable. One limitation of RS-485 signaling is that a maximum of 256 devices can be attached to single network segment. To overcome this limitation a hierarchical network of RS-485/MODBUS segments was designed with multiple gateways (sub-networks), arranged in a tree structure under the master. The first network segment connects the master to all the gateways. Nodes are uniquely identified by a source routing technique that specifies a gateway-node pair. A gateway receives a message from the master, partially unpacks it and transmits a new message to the designated node on its network segment. The process is reversed when the control node sends a response to the master. This approach was deployed with a master, 14 gateways and each gateway having 40 or 50 valve control nodes. Although in this implementation only two network layers are used, the hierarchical structure scales to allow approximately 256D MODBUS devices, where D is the depth of the hierarchy.

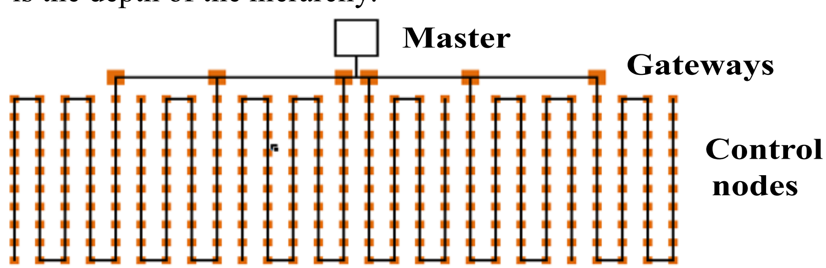

Fig. 2. Communication network section representing the master, six gateways and 270 control nodes in 27 vineyard rows. There are either 40 or 50 nodes, corresponding to 4 or 5 rows, attached to each gateway and connected with 800 to 1000 meters of continuous cable in a serpentine pattern.

Another role of the gateway is to capture water meter readings. At the beginning of each row, defined as the location where water is supplied to each irrigation line, the 4 or 5 line groups are connected to a single water supply line that has a water flow meter to track water delivered through that particular line group. The water flow meters have a resolution of 0.1 gal min^{-1} and a real time count of gallons passed is fed to the gateway. The master queries each gateway for this reading to construct a total water usage figure.

Co-located with the master in the vineyard is a PC that can be accessed remotely through a cellular link connection that allows remote desktop operations. The weekly irrigation schedule can be uploaded in advance and the scheduling started in advance. Irrigation frequency can also be scheduled as a single period or divided into multiple periods per day. Multiple periods provide flexibility to irrigate half of the time in the morning and half in the afternoon. Additionally the irrigation schedule can be suspended in case of rain.

Irrigation scheduling

Irrigation of the 140 zones in the VRI area is scheduled weekly using METRIC (Mapping evapotranspiration at high resolution and internalized calibration), a satellite-based image-processing model for calculating evapotranspiration (ET) as a residual of the surface energy balance (Allen, Tasumi, and Trezza 2007). METRIC solves the energy balance at the Earth's surface, accounting for all major sources (net Radiation, Rn) and sinks (latent heat flux, LE; sensible heat flux, H; and soil heat flux, G) of energy. LE, which is equivalent to Rn – G – H, is converted to ET based on the latent heat of vaporization and density of water. METRIC is applied using multispectral Landsat satellite imagery representing the visible and infrared regions of the electromagnetic spectrum, a digital elevation model, surface roughness estimated from gridded land use data, and CIMIS weather data (CIMIS 2014). The primary output is actual evapotranspiration (ETa) at the pixel scale. The following equation is applied to water each zone: ETc = (ETref) (Kc) (Km), where, ETc = crop evapotranspiration, ETref = reference crop evapotranspiration, Kc = crop coefficient (increases with canopy development), and Km = management factor (changes over time). As mentioned above, the 140 VRI zones are derived from 35 Landsat pixel geolocations (30 x 30 m), each one split into four, 15 x 15 m zones. During irrigation scheduling using METRIC, this splitting is performed at the end of the above calculations by interpolating the final ETc values using Manifold System GIS software (v.8, Manifold Net Ltd., Carson City, NV, USA). A weekly irrigation script, listing hours of irrigation per zone per week is then locally or remotely fed to the irrigation program which runs in the computer located in the field control panel (master control).

The 2013 irrigations started on 2013-04-29 in the zones with yields below the 19.9 t ha^{-1} average (64 zones based on the 2012 yield map). Management factor was 1.2. Four weeks later, on 2013-05-28, irrigation started on the remaining zones (76 zones with yields above average based on the 2012 yield map). At this point the management factor in all zones was set at 0.5 and remained so for four weeks until 2013-06-24, when it was switched to 0.7 in all zones until the end of the season (16 weeks). Scheduled weekly irrigation hours were spread during five to seven days, depending on the expected weather for the ensuing week.

The irrigation system was monitored daily during irrigation days both remotely (online) and in the field by foot. Flush cycles were performed at the beginning, at the middle and at the end of the season. Winterization was performed in November and consisted on installing insulating jackets around large valves and flow meters, air-flushing as much as possible to evacuate all the water in the system, and installing insulating foam tubes around the check valves.

Data acquisition

The 2012 season was the first of a four year plan of study for this vineyard. A panel of measurements, which included several canopy, yield, soil, tissue, fruit and wine quality variables, was performed in 2012 and 2013 in order to characterize within-vineyard variability. Only yield, canopy reflectance and water use are presented and discussed in this report.

Airborne canopy reflectance data was contracted from an outside vendor (C3 Consulting, LLC, Madison WI) and captured after veraison or E-L stage 35 (Coombe and Dry 2004) when the canopies had reached their maximum expansion. Four images, panchromatic, NIR, red, and green, were captured by aircraft at a 75 cm resolution. NDVI (Normalized Vegetation Index) was calculated per pixel from the reflectance values of the NIR and red pixels as (Rouse et al. 1973): NDVI= (NIR-Red) $(NIR+Red)^{-1}$. Since the imaging data was not calibrated to true reflectance, the NDVI values were normalized to percent of the maximum value for each year in some of the analyses. In addition to NDVI values, TVI (Targeted Vegetation Index) values were also sourced from the same vendor. TVI values are the product of their proprietary "PurePixel" image processing procedure. The "PurePixel" procedure uses a biophysical calibration such that values are relatable to adjacent fields and from year-to-year. It also isolates the canopy pixels from the soil, shadow, cover crop and mixed pixels. TVI values will typically range from 100 to 225. The 100 value would represent bare soil while 225 would represent extremely vigorous vegetation. In general, most mature and healthy vineyards will have values between 150 and 200. NDVI and TVI values were mapped and interpolated at 3 x 3 m resolution using an appropriate kriging protocol with VESPER Version 1.62 software (Minasny, McBratney, and Whelan 2005).

Vineyard attributes were studied either on a whole vineyard basis, in the case of yield, soil properties, and canopy reflectance, or via sampling points dispersed throughout the block. For the latter measurements, the 2012 yield map was used to develop a stratified sampling scheme with 36 data pods located throughout the vineyard, corresponding to 12 areas each of relatively low, medium and high yield based on the 2012 map. Pod size was five contiguous vines. Coordinates of the data pods were matched to the high spatial resolution data for yield, soil, and canopy reflectance in Manifold System GIS software. Values for five neighboring points were extracted for each data pod and averaged to obtain a mean value for these attributes. Likewise, measurements on each of the five vines in the data pod were averaged for each attribute. This enabled a complete dataset to be generated for comparison of all attributes in each of the data pods. When necessary, individual data points were geo-referenced in the field using a Case IH AFS AgGPS 162 (CNH Global N.V., Amsterdam, Netherlands) combined receiver and dGPS with positional accuracy of ±50 cm.

Clusters per vine, berries per cluster and berry weight, were measured destructively by removing all the fruit from each data pod just prior to commercial harvest. The number of berries per cluster was calculated from a subsample of 20 randomly selected clusters. 10 berries were removed from the tip of each of these clusters and weighed. A mean berry weight was next calculated, by dividing this weight by 200 (the number of berries). For each yield class, another random sub-sample of 10 clusters was taken, weighed and de-berried. The rachises were then weighed and a mean percent rachis weight was calculated for each yield class. The number of berries per cluster was the calculated by dividing the weight of all clusters (minus the percent rachis weight) by the mean berry weight.

Tonnes per hectare were captured spatially on 2012-10-21 and 2013-10-9 (E-L stage 38) by yield monitoring at harvest (Bramley and Williams 2001). Prior to harvest, yield monitor systems were installed on two models of over-the-row trunk-shaking mechanical harvesters: GH9000 self-propelled AIM harvesters (Ag Industrial Manufacturing, Lodi, CA, USA) and 800 Series pull-behind VineStar harvesters (Grapekist, Madera, CA, USA). Yield monitor systems consist of the combined dGPS receiver and antenna as well as a specialized yield monitoring system for grape harvesters – a load cell weight bridge, belt speed sensor and data logger – produced by Advanced Technology Viticulture (ATV, Joslin, Australia). Geo-referencing of data points is accomplished by simultaneously logging the coordinates of each measurement with the dGPS. The data logger records the data on a high definition card. The data is transferred to a personal computer and accessed using proprietary software from ATV. Belt scales are zeroed before each harvest and the system is calibrated against actual truck weights at the beginning of the harvest season and weekly thereafter. The calibration is considered acceptable when the display weight error ranges are within 8% of the winery weight, but consistent monitoring outperforms the acceptable range with an error of no more than 3-4%. Harvest data is transferred into a clean-up script written in R Studio software (RStudio Inc., Boston, MA, USA) to convert mass flow units into tons per acre, eliminate outliers, and normalize harvesters. Yield data points more than three standard deviations from the mean are removed to reduce scatter which usually results in less than five percent of total yield point removal. After clean-up, data were transferred into VESPER Version 1.62 (Minasny, McBratney, and Whelan 2005) for kriging to 3 x 3 m resolution. The raster datasets were transferred into the GIS program (Manifold System, Manifold Net Ltd., Carson City, NV, USA) for interpretation and comparison with other variables.

To compare the effect of VRI with CI on variability of vineyard attributes, a second 4.05-hectare section was delineated on the area immediately adjacent to the south edge of the VRI area (Figure 1). Irrigation treatment effects were analyzed using the 3 x 3 m data or their average for each 15 x 15 m irrigation zone. Non-spatial statistics were also used to measure the effect of irrigation on yield and canopy reflectance, specifically, the coefficient of variation (CV) and the spread, the latter calculated as the range divided by the median (Bramley, Lanyon, and Pantnen 2005). Variogram parameters were obtained from VESPER (Minasny, McBratney, and Whelan 2005) to calculate spatial statistics for yield, NDVI and TVI. Qualitative spatial indices included the Cambardella index, CmbI (Cambardella et al. 1994), and the mean correlation distance, MCD (Han et al.

1994). Variograms were constrained to a range of 120 m to focus on short to medium range spatial variation. Values of the CmbI were assessed as less than 25 indicating strong spatial dependency, 25-75 indicating moderate spatial dependency, and greater than 75 indicating weak spatial dependency. Higher MCD values were equated to more spatial structure.

RESULTS AND DISCUSSION

System performance

The irrigation system was assembled using commercially available components that performed very well in general. Some of them failed sporadically but where quickly identified during the daily inspections and fixed or replaced. The most common performance failure were solenoid valves not completely closing at the end of irrigation cycles, but this amounted up to just 0.5% over-irrigation. These leaks were caused either by accumulation of debris at the valve, valve failure, or software-related communication issues between the control boxes and the valves. While this prototype served very well its proof of concept purpose, its cost would be unsustainable if used commercially with the same components and level of monitoring. A sustainable commercial version would have to be highly optimized, ruggedized and modularized in a much simplified package, with all power and communications elements embedded in the modules.

Effect on vineyard variability and water use efficiency

Figure 3 shows the yields of the VRI area compared to the CI area selected for comparison purposes (as "control"). While the overall yield for the entire vineyard block decreased from 17.9 t ha^{-1} in 2012 to 15.7 t ha^{-1} in 2013, the reduction in yield was smaller with VRI (14%) compared to CI (17%, Table 1).

There was an overall reduction in spatial variability from 2012 to 2013 in VRI compared to CI. Field variability in yield, NDVI and TVI was lower during 2013 in VRI compared to CI, as indicated by the non-spatial coefficient of variation (CV) and spread statistics (Table 1). While variability in NDVI and TVI was lower in VRI compared to CI in 2013, there was a decrease in NDVI and an increase in TVI in 2013 compared to 2012. Since TVI uses the "PurePixel" procedure for extraction of canopy-only pixels out of the image layers used for calculating NDVI, it may be accounting for the progress of bot canker, a fungal disease caused by *Botryosphaeria* sp. and endemic in California vineyards 20 years and older. Bot canker kills entire cordons or cordon sections and is a major contributor to vine to vine variability.

The analysis of spatial variability in both years indicates that in general the VRI decreased field spatial structure and dependency (Table 2). The MCD was similar for both years in NDVI and TVI for CI and lower in 2013 for VRI. However, in all cases it was much lower in VRI compared to 2012, indicating less spatial structure under VRI in 2013 and relative to CI. The CmbI decreased in 2013 vs. 2012 for yield, NDVI and TVI in CI suggesting stronger spatial dependency in 2013 for CI; however in the VRI it remained the same for TVI, increased moderately for NDVI and increased significantly for yield. The above changes in CmbI indicate that VRI decreased spatial dependency.

Since there was an overall reduction in block yield from 2012 to 2013, the decrease in yield variability by VRI compared to CI could be explained by the reduction of yield in the higher yielding irrigation zones and a slight increase or no change in yield in the low yielding zones. Even though the low yield zones received up to 17% more water than the high yield zones, a significant increase in yield cannot be expected after just one year of increasing irrigation rates. Any increase in yield due to irrigation after just one season can only be due to an increase in berry weight, the only yield component that varied significantly among yield classes in both VRI and CI (data pod measurements, Table 3).

Water use efficiency was higher in VRI than CI (Figure 4) which could be the result of comparatively higher yields in low vigor areas in the VRI section of the field compared to the CI and the more targeted, data-driven application of water based on canopy metrics and energy balance used by the METRIC model and only possible under a variable rate irrigation regime.

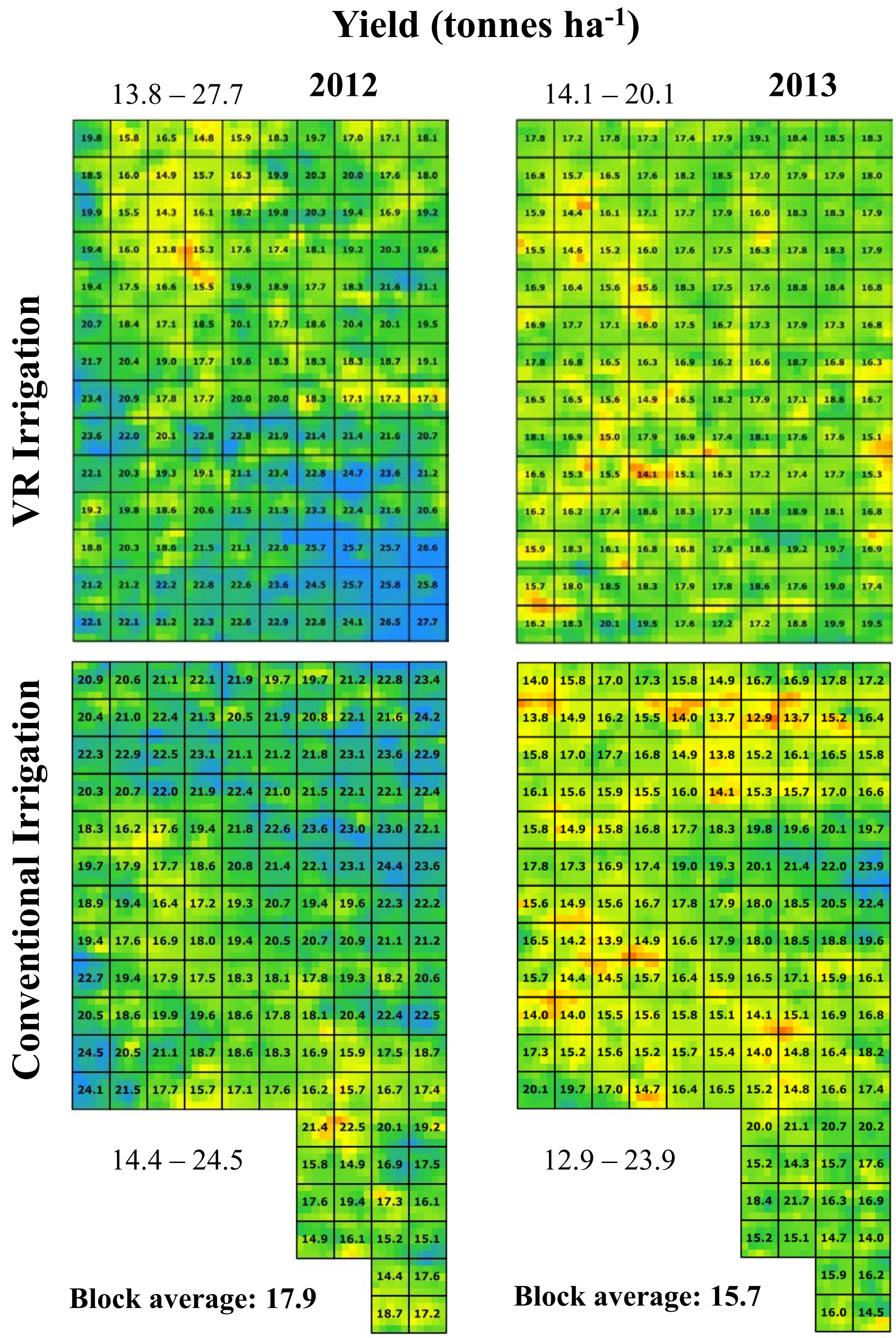

Fig. 3. 2012 and 2013 yields of the variable rate irrigated area compared to the conventional irrigation "control" area. Yield ranges in each treatment/year are for individual data pixels. Numbers in the center of each zone are average t ha^{-1} for that zone.

Table 1. Non-spatial statistics of yield, NDVI, and TVI in the variable rate and conventional irrigation treatments, and changes (Δ) in 2013 from 2012.

		Average			C.V. (%)			Spread		
		2012	2013	Δ	2012	2013	Δ	2012	2013	Δ
Yield	VRI	20.04	17.27	-14%	14.06	6.82	-51%	0.70	0.35	-51%
	CI	19.89	16.61	-17%	12.18	12.34	1%	0.50	0.68	36%
NDVI [1]	VRI	0.83	0.84	1%	7.01	4.42	-37%	0.36	0.19	-45%
	CI	0.83	0.86	4%	5.73	4.47	-22%	0.36	0.29	-19%
TVI	VRI	174.41	176.53	1%	1.30	1.67	29%	0.07	0.08	20%
	CI	174.85	177.93	2%	1.22	1.77	45%	0.07	0.10	52%

[1] Fraction of maximum NDVI for each treatment

Table 2. Spatial statistics of yield, NDVI, and TVI in the variable rate and conventional irrigation treatments, and changes (Δ) from 2012 to 2013.

		MCD			CmbI		
		2012	2013	Δ	2012	2013	Δ
Yield	variable rate	50.25	11.12	-78%	6.20	17.75	186%
	conventional	43.38	32.84	-24%	6.36	4.48	-29%
NDVI	variable rate	53.73	29.85	-44%	8.81	10.25	16%
	conventional	33.21	33.03	-1%	16.38	8.51	-48%
TVI	variable rate	31.18	21.41	-31%	16.02	15.94	0%
	conventional	37.26	37.23	0%	28.93	16.10	-44%

MCD = mean correlation distance   CmbI = Cambardella index

Table 3. Canopy and yield component variables from data pods in the variable rate (VRI) and conventional (CI) irrigation treatments.

Irrigation	Yield class	Leaf area index	Clusters per vine	Cluster weight (g)	Berry weight (g)	Ravaz index	Yield (t ha^{-1})
VRI	high	6.0 a	147.7 a	76.0 a	0.9 ab	2.8 a	19.1 abc
	medium	5.3 a	127.7 a	84.7 a	0.8 b	3.2 a	17.7 abc
	low	5.2 a	127.7 a	71.6 a	0.7 c	2.4 a	15.7 bc
CI	high	6.1 a	151.6 a	81.9 a	1.0 a	2.8 a	20.8 a
	medium	6.1 a	155.6 a	75.7 a	0.8 b	3.0 a	19.5 ab
	low	6.1 a	130.2 a	66.1 a	0.7 bc	2.6 a	14.8 c

Treatment averages with different letters are significantly different at $p<0.05$
Ravaz index = ratio of vine yield to vine pruning weight

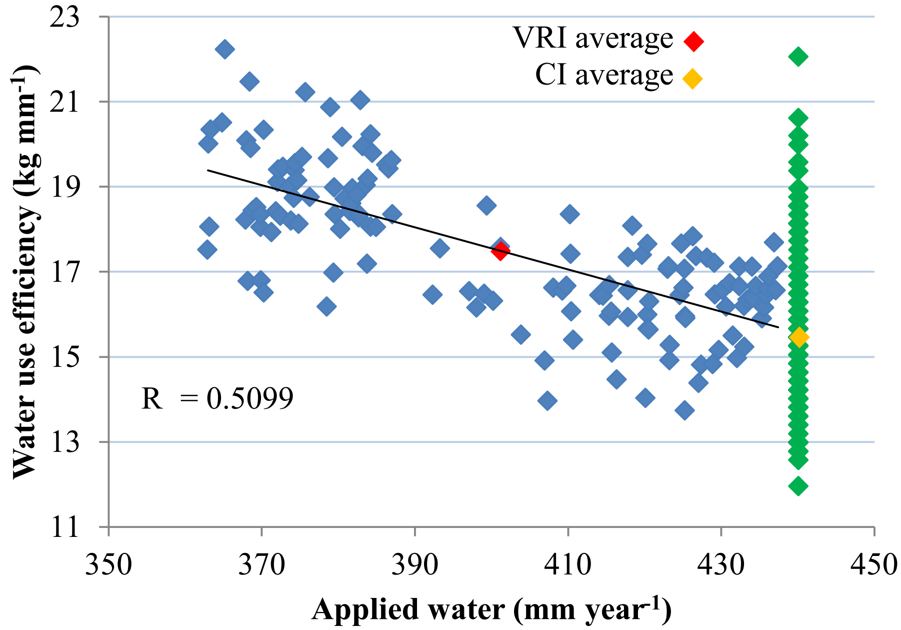

Fig. 4. Water use efficiency for the variable rate and conventional irrigation treatments (blue and green symbols respectively).

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