Remote sensing tools for water use efficiency of grapes in the Winelands Region, Western Cape

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Abstract

Since the grape industry is vitally important to the economy of the Western Cape in South Africa, the challenge is to maintain it economically sustainable whilst making optimum use of the limited water resources. This study aims at estimating total evaporation (ET), grape yield and water use efficiency (WUE) of table and wine grapes, spatially. The Surface Energy Balance Algorithm for Land (SEBAL) was applied on 12 Landsat images to estimate ET and yield and was calibrated with field observations. ET calculated with SEBAL was within 18 % of that measured in the field. Wine and table grape yields were within 5 % of that measured in the field. WUE was fairly constant among seasons and on average 3.8 and 4.7 kg/m^3 for table and wine grapes respectively. SEBAL is a tool that enables farmers to manage their water resources more productively as SEBAL shows where WUE can be improved.

Keywords: water use efficiency, grape yield, remote sensing, water management

1. Introduction

South Africa is an arid country with an average annual rainfall of about half the world average of 900 mm/yr. South Africa can be classified as a "water stressed" country. It is envisaged that competition for water between different uses will continue to increase in future. Most of the grape producing areas in the Western Cape is highly dependent on irrigation water. As the water usage by the agricultural sector of the Western Cape is significant (67 % of the total water use) this sector needs to be actively involved in finding solutions to a looming water shortage crisis (Roux, 2006). The amount of water required by irrigated agriculture needs to be reduced, whilst the grape industry is maintained economically sustainable. It is therefore essential to use the limited resources optimally. Information on the water use efficiency of different crops, farms and irrigation blocks are required to suggest improvement in the water utilization. In South Africa the National Water Act (1998) demands the economical and sustainable usage of water, the efficient management of water usage and prevention of ineffective water usage. Proof on the efficiency of existing water usage is required before licenses for the use of water will be issued or renewed in future (Roux, 2006). Information on water use efficiency (WUE) is often available for single fields, so the results are relevant to the local area only. WUE can vary from year to year depending on site specific conditions (soil, crop type) as well as climatic conditions and water management practices. The use of Remote sensing technologies makes it possible to estimate and evaluate water use efficiency spatially and temporally.

This paper aims at illustrating the use of a remote sensing technology to evaluate the water use efficiency of grapes, so farmers can be informed on how productively they are managing their available water resources.

2. Materials and methods

2.1 Research area

The Western Cape Province of South Africa hosts the country's major vineyards and wine industries. The grape producing areas of the Western Cape in South Africa are an important contributor to the economy of this province. Both wine and table grapes are produced extensively, but other fruit crops are also grown. Four grape producing areas in the Western Cape Province were selected for this study: the Hexriver valley, Paarl, Worcester and Franschhoek (Figure 1). Table grape production specifically is highly dependent on irrigation water. Irrigation water often originates from different sources e.g. groundwater, irrigation schemes, private bore holes and dams. In the Western Cape, most irrigation water is applied from November to January. In some areas grapes are irrigated in winter to prevent early budding. The grape growing season

normally extends from September to April. The date of grape harvest differs considerably between the different study areas and for different cultivars.

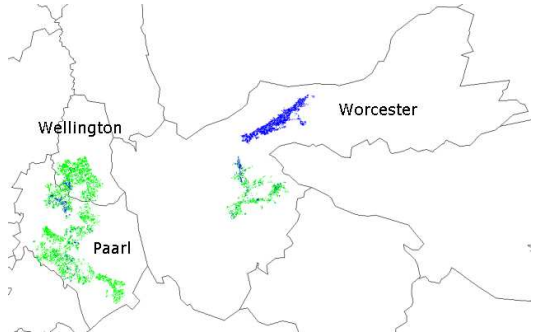

Figure 1 The location of the four grape producing areas (Hex river valley, Paarl, Worcester and Franschhoek) in the three districts (Wellington, Paarl and Worcester) selected for this study

2.2 Research approach

The Surface Balance Algorithm for Land (SEBAL) is used to estimate total evaporation (ET) and water use efficiency for grapes in the Hexriver valley, Paarl, Worcester and Franschhoek areas for two growing seasons (September 2004 to April 2005; September 2005 to April 2006).

2.2.1 Total evaporation estimation

SEBAL uses the simplified energy balance to estimate total evaporation (ET or the latent heat flux density, λE), biomass production, water deficit and soil moisture spatially. Bastiaanssen et al. (2002; 2005) and Allen et al. (2005; 2007) describes SEBAL in great detail. Land surface characteristics such as surface albedo, the vegetation index and surface temperature are derived from satellite imagery. In addition to satellite images SEBAL requires meteorological data (wind speed, humidity, solar radiation and air temperature). Since SEBAL uses the energy balance, and not the water balance, no data on land cover, soil type or hydrological conditions are required. The simplified energy balance is given by

$$\lambda E = R_n - G - H$$

where R_n (W m^{-2}) is the net irradiance, G (W m^{-2}) is the soil heat flux density and H (W m^{-2}) is the sensible heat flux. Storage of energy in the canopy is considered to be small and is ignored. R_n is computed from solar irradiance, the surface albedo, vegetation index and surface temperature. G is estimated from R_n, surface temperature and the vegetation index. H is estimated from surface temperature and roughness, and windspeed. Prior to the spatial estimation of λE, "extreme" values of H are computed, e.g. for a water surface (H=0) or a desert ($H=R_n-G$).

2.2.2 Biomass, Harvest index and Yield calculation

Biomass production calculated by SEBAL can be defined as the total dry matter production by a plant (roots, stems, leaves and fruit). The above ground biomass is a function of incoming shortwave radiation at the top of the atmosphere, atmospheric transmissivity, maximum light use efficiency, the fraction of APAR/PAR, the stomatal response to ambient temperature, the slope of saturated vapour pressure curve, the psychrometric constant and the surface, minimum surface resistance and aerodynamic resistances. This biomass function is described by Zwart and Bastiaanssen (2007).

The harvest index (HI) indicates the part of the biomass that is harvested. In this study this index is an empirical function of water deficit in February ($ETdef_{Feb}$ in mm/mth) and moisture content in November and December (Θ_{Nov}). The HI function for table grapes is based on field measurements of yield in the Hexriver valley (n=31). The final table grape yield depends on the biomass (in kg/ha), HI and the moisture in the grape berries, which was fixed at 25%. The constant a was 1.5647 for 2004-5 and 1.6686 for 2005-6.

$$HI_{tablegrapes} = (0.1036 \cdot \theta_{Nov}^{-1.215}) \cdot a \cdot ETdef_{Feb}^{0.4}$$

$$Yield_{tablegrape} = (biomass \cdot HI)/(1-0.75)$$

The harvest index (HI) of wine grapes was found to be dependent on the water deficit in February ($ETdef_{Feb}$) and moisture content in November and December (Θ_{Dec}). The moisture content of the grape berries (θ_{grape}) is a function of the soil moisture in March and April (Θ_{Mar}), and therefore variable not fixed as is the case for table grapes. The wine grape yield function is based on field measurements of yield from the Colombar grape cultivar grown in the Worcester area (n=10) and used in the brandy industry. The wine grape yield function needs to be improved to include more cultivars as very different management strategies are applied in the production of different wine grape cultivars.

$$HI_{winegrapes} = (0.16 + 0.03 \cdot \theta_{Dec}^{-1.1}) \cdot 0.91 \cdot ETdef_{Feb}^{0.05} \qquad \theta_{grape} = 4.483 \cdot \theta_{Mar}^{2} - 3.83 \cdot \theta_{Mar} + 1.5499$$

$$Yield_{winegrape} = (biomass \cdot HI) / (1 - \theta_{Mar})$$

2.2.3 Water use efficiency calculations

The spatial estimates of evaporation and yield were used to calculate water use efficiency (WUE in kg m^{-3}) of table and wine grapes. Water use efficiency (or water productivity) is defined as the marketable crop yield per unit of actual total evaporation (ET_{act}):

$$WUE = \frac{10 \cdot yield[kg / ha]}{ET_{act}[mm]}$$

2.2.4 Remote sensing data

SEBAL requires as inputs a number of biophysical parameters which can be derived from satellite images. These include surface albedo, fPAR, emmissivity, evaporation fraction, surface roughness and bulk surface resistance. Different land classes (water, bare soil, fynbos, forest, dryland farming, table grapes and wine grapes) were distinguished on three LANDSAT images covering the Western Cape wine producing areas, using sequential unsupervised classifications (ISODATA clustering). Areas under table grapes were distinguished from wine grapes on the basis of differences in NDVI's. Three 5-TM LANDSAT images were used (September 2004, December 2004 and February 2005) (Table 1). LANDSAT images have a spatial resolution of 30 m, and a temporal resolution of 16 days. As LANDSAT 7-ETM images are scan line corrected for missing pixels, not all the images acquired could be used to generate a land cover map. On the land cover map one can not clearly distinguish vineyards from other orchards and therefore some of the areas classified as table or wine grapes may actually include areas of orchards. Cloud free ASTER images (Table 1), with a resolution of 15 m, in combination of three LANDSAT 5-TM images, were used to distinguish table and wine grapes from other orchards and to further improve the grape map for the four study areas. The ASTER images overlap with the LANDSAT images but only cover the four study areas. All the images were geo-referenced to topographic maps (1:50 000 and 1:100 000).

SEBAL results were analysed with the land cover map created from the LANDSAT and ASTER images. Since vineyards are perennial, only one land cover map was used for both study years.

Table 1 Satellite data acquired by the ASTER and LANDSAT sensors. Four ASTER (of two dates) and 12 LANDSAT images were acquired. The satellite images were obtained for periods corresponding to the different growing seasons studied and used in the SEBAL calculations.

Satellite data used (ASTER and LANSAT images)			
Satellite	Satellite image	Acquisition day of year and time	Representative period
TERRA	ASTER	16 March 2005	March 2005
	ASTER	23 March 2005	March 2005
LANDSAT IMAGES (5-TM and 7-ETM: path 175, row 83)	TM5 20 Sept 2004	264; 08:19	September 2004
	ETM7 30 Oct 2004	304; 08:24	October 2004
	ETM7 15 Nov 2004	320; 08:24	November 2004
	TM5 9 Dec 2004	344; 08:21	December 2004
	ETM7 18 Jan 2005	018; 08:24	January 2005
	TM5 27 February 2005	058; 08:22	February 2005
	ETM7 23 March 2005	082; 08:25	March & April 2005
	TM5 9 October 2005	282; 08:23	September & October 2005
	ETM7 4 December 2005	338; 08:25	November 2005
	ETM7 20 December 2005	354; 08:25	December 2005
	ETM7 6 February 2006	037; 08:25	January and February 2006
	ETM7 10 March 2006	069 08:25	March and April 2006

2.2.5 Spatial extrapolation of climatic data

SEBAL requires as input spatial estimates of air temperature, humidity, windspeed and solar radiation, i.e. an estimate for each LANDSAT pixel used. Climatic data from weather stations on the ground was available for the study areas. The Meteolook algorithm (Voogt, 2006), a method of interpolating and extrapolating climatic point data on the basis of physiographical properties, was used. Meteolook requires information on several terrain variables. Albedo and roughness length are derived from the land cover map. The accuracy of the solar irradiance estimates, an important input to SEBAL, was checked against the theoretical clear sky solar radiation. Only 15 weather stations passed the quality control test. The accuracy of the spatial interpolating and extrapolating of climatic point data using Meteolook was tested. Meteolook was also tested to see if it can predict micrometeorological conditions in irrigation blocks accurately.

3. Results

3.1 Accuracy of the land cover classification

The accuracy of the land cover map used in the SEBAL modelling is critical for the accurate estimation of spatial total evaporation and yield. Areas under table grapes were classified to an accuracy of 94 % for the four study areas. Areas under wine grapes (including bush grapes) were classified to an accuracy of 78 %. As table grapes are generally grown on horizontal trellis systems, which result in a near complete soil cover during the growing season, table grapes can be distinguished easily from other orchards. However, wine grapes are grown in rows covering the soil only partially. Wine grapes therefore appear similar to orchards from space and are therefore more difficult to distinguish from orchards.

3.2 Accuracy of meteorological data extrapolated with the Meteolook algorithm

Temperature and relative humidity predictions with Meteolook were validated against independently collected data. Though differences existed, the air temperature and relative humidity predicted with Meteolook for most stations was within 1 °C and 15 % respectively for air temperature and relative humidity. Three mechanical weather stations (Ideal Hill, Mountain Vineyards, Villiersdorp) located in the vineyards were used to validate the robustness of Meteolook in predicting micro-meteorological conditions in irrigation blocks. The Meteolook predicted temperatures in the irrigation blocks were slightly lower than the measured temperatures (slope 0.997).

3.3 Total evaporation

Total evaporation was calculated with SEBAL for the entire Landcover map area overlapping the four study areas (Hexriver valley, Paarl, Franschhoek and Worcester) (Figure 2). Total evaporation (ET) is calculated for the growing seasons (September to April) of 2004-5 and 2005-6.

The accumulated ET calculated with SEBAL and that with a field water balance for table grapes in the Hexriver valley compares well (Figure 3). Without calibration or parameter optimization, the accumulated table grapes ET estimated with SEBAL exceeded that estimated with the field water balance by 80 and 3 mm in 2004-5 (October to February) and 2005-6 (September to April) respectively. Bigger differences existed between the monthly ET's estimated with SEBAL and the water balance (Figure 3). In both years, the monthly ET at the beginning of the growing season estimated with SEBAL was less than that estimated with the field water balance. At the end of the season, the SEBAL estimate of ET exceeded the field water balance estimate. At the beginning of the growing season, the vines just emerge from a dormant phase and a relatively large amount of irrigation water is generally available and applied, often resulting in over irrigation at this time.

The average accumulated wine grape ET estimated with SEBAL in 2004-5 (September to April) was 734 mm, which is 113 mm more than that calculated with the simplified water balance (Figure 4). At the beginning and the end of the growing season, the monthly wine grape ET's estimated with SEBAL were less that estimated with the water balance.

The average SEBAL calculated ET's for the growing seasons of 2004-5 and 2005-6, show that table grapes consume more water than wine grapes (Figure 5). The average SEBAL ET's for the entire table grape growing areas were 702 and 828 mm for the growing seasons of 2004-5 and 2005-6 respectively (Figure 5). This was considerably higher than the SEBAL ET's for the wine grape growing areas: 533 and 575 mm in 2004-5 and 2005-6 respectively, suggesting that wine grapes in general, are more conservative users of water than table grapes. Both table and wine grapes consumed more water during 2005-6 than in 2004-5: 18 % (126 mm) and 8 % (42 mm) for table and wine grapes respectively. The increased table grape ET (2004-5 to 2005-6) corresponds well with the increase of 169 mm in the irrigation water applied in the Hexriver valley area.

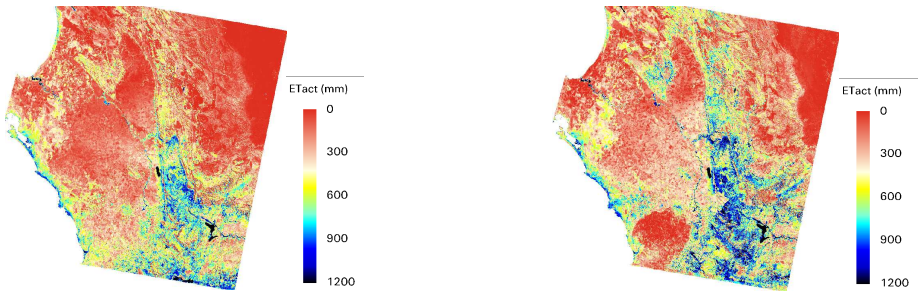

Figure 2 Total evaporation estimated with SEBAL for the periods September to April of 2004-5 (left) and 2005-6 (right) for an entire LANDSAT image

Table and wine grape ET shows a greater variation in 2005-6 than in 2004-5, with standard deviations in the ET's of 171 and 218 mm for table and wine grapes respectively in 2005-6, and standard deviation of 111 and 170 mm for table and wine grapes respectively in 2004-5. The bigger variation in ET's of both table and wine grapes in 2005-6, suggests that not all farmers were able to increase their irrigation supplies despite a wetter year. The standard deviation of the total evaporation of wine grapes (170 and 218 mm) is higher than that of table grapes (111 and 171 mm) for both years studied. This can be explained by the fact that different wine grape cultivars require different irrigation strategies, with a tradeoff between quality and quantity production. The coefficient of variation in ET of wine grapes and table grapes reflects this (0.349 for wine grapes vs. 0.182 for table grapes).

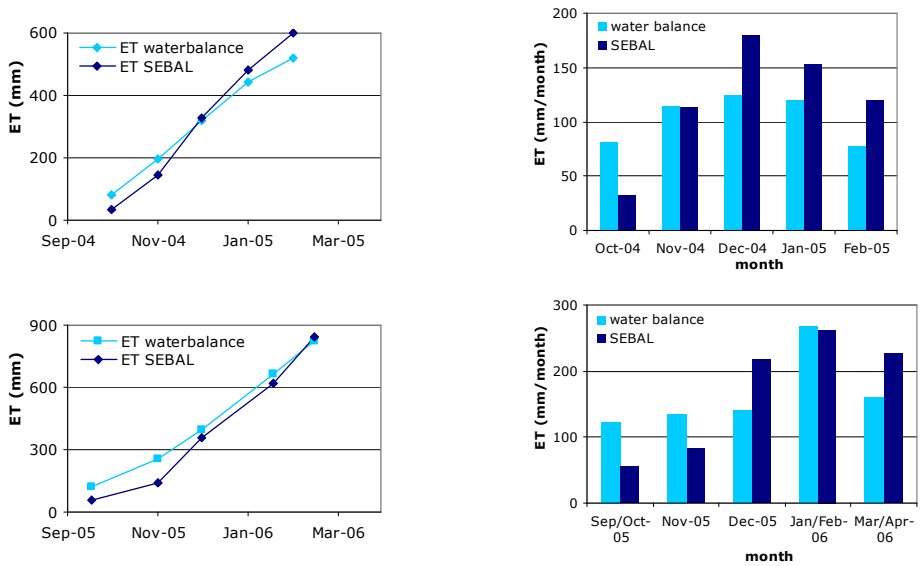

Figure 3 Monthly total evaporation and accumulated total evaporation of table grapes in the Hexriver valley in 2004-5 (top) and 2005-6 (bottom). ET is calculated with SEBAL and the soil water balance (field data).

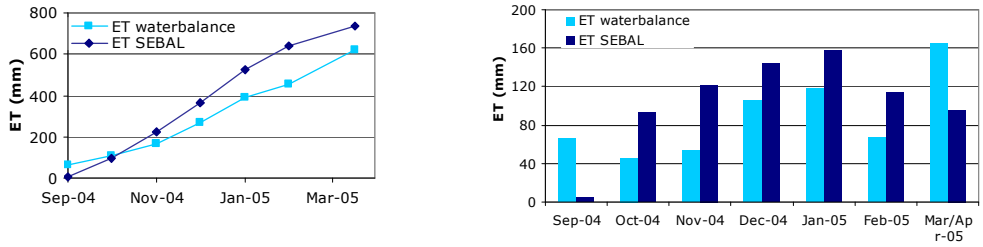

Figure 4 Monthly total evaporation and accumulated total evaporation of wine grapes in the Worcester area in 2004-5. ET is calculated with SEBAL and the soil water balance (field data).

3.3.1 International estimates of grape total evaporation

The total evaporation of table grapes in the Hexriver valley and wine grapes in Worcester compares well with total evaporation rates estimated in regions with a Mediterranean climate. Williams et al. (2003b) used lysimeters to determine water use (from budbreak until the end of October) of Thompson Seedless grapevines in California. The total evaporation of the vines was 718 and 865 mm, which fall within the range of total evaporation for the table grape producing area Hexriver valley (599 and 830 mm). Yunusa et al. (1997b) found ET's between 2 mm d^{-1} in spring and 5 mm d^{-1} in summer for Sultana vine grapes in Australia, which is lower than the daily maximum rates estimated for table grapes of the Hexriver valley (5 to 7 mm d^{-1}).

Total evaporation measured in Israel (even more arid conditions) exceeds the total evaporation rates measured in Worcester. Maximum total evaporation of drip irrigated grapevines in Israel, ranged from 7.6 to 8.2 mm d^{-1} (Netzer et al., 2005), and compare well to maximum daily total evaporation estimated in Worcester which remained below 7.6 mm d^{-1}. Total evaporation estimates in areas with a more humid climate, such as Brazil and France, the total evaporation estimated for grapes were lower than that estimated in South Africa. De Castro Texeira et al. (paper submitted) measured actual ET's of drip-irrigated table and wine grapes in Brazil during the growing season. In his experiments total evaporation of young table grapes was 352-393 mm, while the total evaporation of wine grapes was between 438 and 517 mm on average, well below

the results for Western Cape Province. Trambouze et al. (1998) measured actual ET's of an un-irrigated Shiraz vineyard in southern France. ET's ranged between 1.6 mm d^{-1} and 3.4 mm d^{-1}, which is less than that estimated for wine grapes of South Africa.

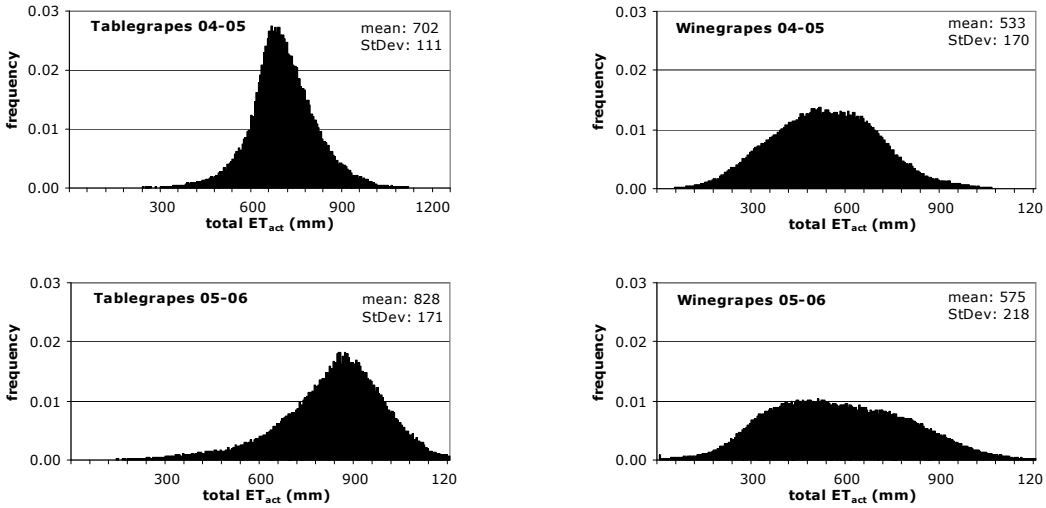

Figure 5 Frequency distributions of total evaporation of wine and table grapes during the growing seasons of 2004-5 and 2005-6 for the four study areas: Hexriver valley, Paarl, Franschhoek and Worcester

3.4 Biomass and grape yield

Biomass is calculated with SEBAL for the entire Landcover map area overlapping the four study areas (Hexriver valley, Paarl, Franschhoek and Worcester) (Figure 6). Accumulated biomass is estimated for the growing seasons (September to April) of 2004-5 and 2005-6.

Table and wine grape yields in the Hexriver valley, Paarl, Francshoek and Worcester show variation between the two growing seasons (Table 2). Most of the table grapes are produced in the Hexriver valley, where the average yield is lower than in the Paarl area. No table grapes are produced in Francshoek and only a small area (7ha) in the Hexriver valley is under wine grapes. Table grape production in 2005-6 was on average 5 and 2.9 ton ha^{-1} (for the Paarl and Hexriver valley areas respectively) higher than in 2004-5. The yield decreased by nearly 6 ton ha^{-1} in the Worcester area during the corresponding period (Table 2).

Wine grape yield did not show a great variation between the different areas and years studied. Grape yield ranged between 20 and 25 ton ha^{-1}. Franschhoek shows the highest wine grape yield in both years studied (Table 2).

Figure 6 Biomass production estimated with SEBAL from the growing period (September to April) of 2004-5 (left) and 2005-6 (right) for the LANDSAT image covering the four study areas

Table 2 Table and wine grape yield for the four study areas for the growing seasons (September to April) of 2004-5 and 2005-6

	Paarl		Worcester		Hex Valley		Franschhoek	
	table	wine	table	wine	table	wine	table	wine
area (ha)	1169	12720	639	2898	4231	7	0	1599
yield 2004-5 (kg ha^{-1})	28889	23497	21742	22928	25661	20712	0	25164
yield 2005-6 (kg ha^{-1})	33924	22900	15649	24577	28588	22967	0	24669

The average table grape yield measured in the Hexriver Valley in 2004-5 and 2005-6 was 28,494 kg ha^{-1} and 25,563 kg ha^{-1} respectively, and compared well with SEBAL yield calculations for the same field where measurements were made (27,277 kg ha^{-1} and 24,251 kg ha^{-1} for 2004-5 and 2005-6 respectively) (Figure 7). The spatially modeled yield was on average 5 % lower than the measured yield. Measured table grape yield is based on yield estimates for 32 irrigation blocks in the Hexriver valley area. The average wine grape yield measured in the Worcester areas during 2004-5 was 22,623 kg ha^{-1} or approximately 4 % lower than spatial estimate of yield using SEBAL (23,445 kg ha^{-1}) (Figure 8). Measured wine grape yield was only available for 2005 and is based on yields from 10 individual irrigation blocks in the Worcester area.

Figure 9 shows the effect that the area used in the calculation of spatial yield (using SEBAL) has on the accuracy of the yield. In comparing yield measured from small irrigation plots, differences (error) of up to 45 % can exist between measured and modelled. The accuracy of the yield predictions improve when more than one irrigation block are grouped and considered as one single field. Differences in yield (measured vs. modelled) is less than 5 % when the area is 9 ha and 28 ha for wine and table grapes respectively. This means that when measured and modelled yield are compared at individual irrigation block level, yield difference can be significant, but when several irrigation blocks are grouped together the SEBAL modelled yield is quite accurate.

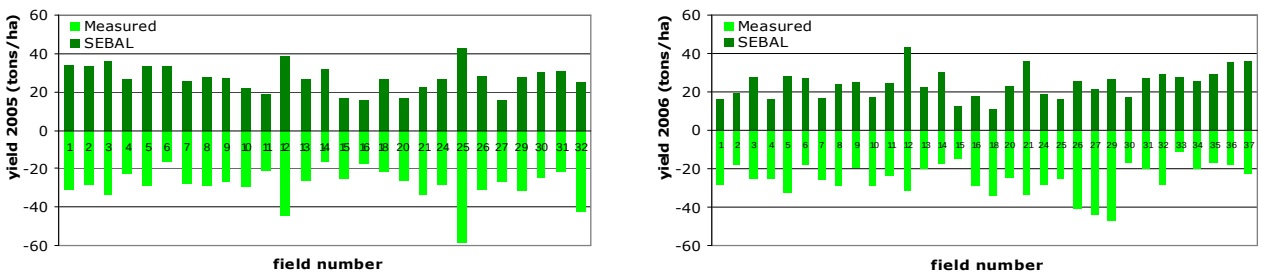

Figure 7 Measured and SEBAL modeled yield for 32 individual irrigation blocks in the Hexriver valley area. Measured yields are shown negatively to aid in comparisons.

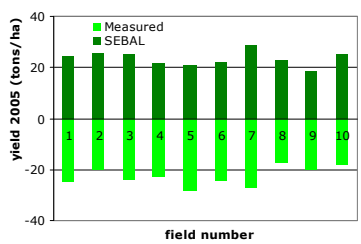

Figure 8 Measured and SEBAL modeled yield for 10 individual irrigation blocks in the Worcester area. Measured yields are shown negatively to aid in comparisons.

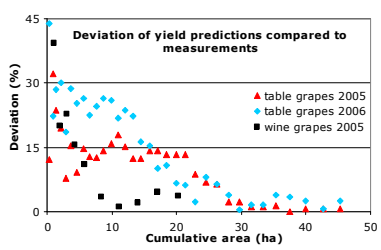

Figure 9 Deviation of spatially estimated yield (using SEBAL) from yields measured for individual fields in the Hexriver valley and Worcester areas

3.5 Water use efficiency

The water use efficiency of table and wine grapes were estimated for the Hexriver valley, Paarl, Franshoek and Worcester areas for the growing seasons of 2004-5 and 2005-6 using SEBAL estimates of ET and yield. In 2004-5 and 2005-6, the water use efficiency of wine grapes was on average higher (1 and 0.8 kg m^{-3} in 2004-5 and 2005-6) than that of table grapes (Figure 10). The water use efficiency of table and wine grapes decreased by 4 and 8 % respectively from 2004-5 to 2005-6 (WUE of table grapes was 3.8 and 3.6 kg m^{-3} and the WUE of wine grapes was 4.85 and 4.47 kg m^{-3}) (Figure 10). Although table grape yield was comparable to the wine grape yield, the total evaporation of table grapes was constantly higher than that of the wine grapes in both 2004-5 and 2005-6 (Tables 2 and 3). This resulted in the differences in the water use efficiencies between table and wine grapes shown in Figure 10 and Table 4.

Water use efficiencies of table and wine grapes varied greatly between different areas (Table 3). The WUE of wine grapes was consistently higher than that of table grapes for all the areas. The water use efficiency of table grapes was the highest in Paarl (4.4 and 4.5 kg m^{-3}). ET of table grapes in Paarl and in the Hexriver valley are similar for 2004-5 and 2005-6 (Table 4), but because the grape yield in Paarl are higher than in the Hexriver valley, the WUE of table grapes in the Hexriver valley is slightly lower than that of the Paarl area, but still favourable. The WUE of table grapes are the lowest in Worcester (1.9 and 2.8 kg m^{-3}) because of high ET and low yields (Tables 2 and 3).

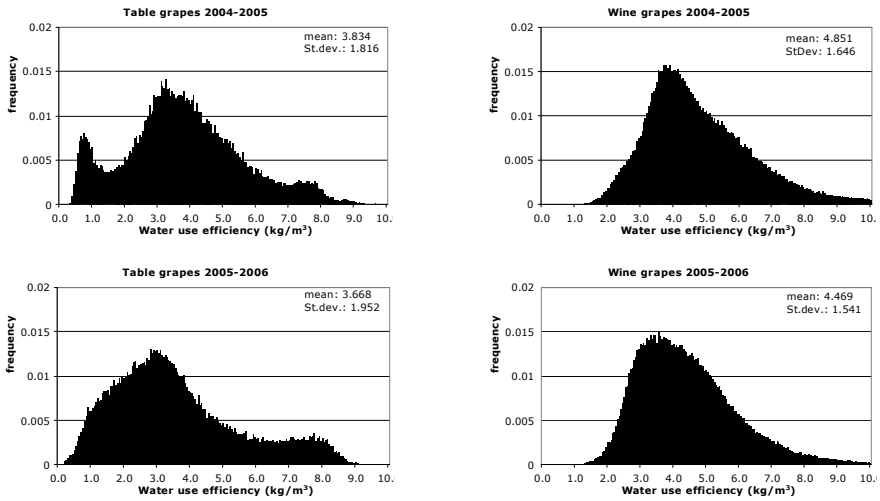

Figure 10 Water use efficiency for table and wine grapes grown in the grape producing areas of the Hexriver valley, Paarl, Franschhoek and Worcester for the 2004-5 and 2005-6 growing seasons

Table 3 Area under grapes, grape yield, water use efficiency (WUE) and total evaporation (ET_{act}) for table and wine grapes in the Hexriver valley, Paarl, Franschhoek and Worcester areas

	Paarl		Worcester		Hex Valley		Franschhoek	
Grape type	Table	Wine	Table	Wine	Table	Wine	Table	Wine
Area (ha)	1169	12720	639	2898	4231	7	-	1599
WUE 2004-5 (kg m^{-3})	4.5	5.3	2.8	3.3	3.8	3.9	-	4.1
WUE 2005-6 (kg m^{-3})	4.4	4.8	1.9	3.5	3.7	3.7	-	3.5
ET_{act} 2004-5 (mm)	684	478	818	716	698	543	-	635
ET_{act} 2005-6 (mm)	833	517	909	738	828	643	-	741

Though the wine grape yield was highest in Franschhoek in both 2004-5 and 2005-6, the highest WUE of wine grapes was estimated for Paarl (5.3 and 4.8 kg m^{-3}). In contrast, the WUE of wine grapes in the Worcester was the lowest (3.3 and 3.5 kg m^{-3}), due to the very high total evaporation in both years (Table 3).

The WUE also varies spatially within a specific area. Figures 11 to 13 show the WUE in the Hexriver valley, Paarl, Franschhoek and Worcester areas spatially. WUE in the most parts of the Hexriver valley decreased from 2004-5 to 2005-6, due to slightly lower yields, but significantly higher ET's (Figure 11). The lower WUE is particularly clear in the downstream area (bottom end of the valley). WUE in 2004-5 and 2005-6 ranged between values of less than 1 kg m^{-3} to values greater than 8 kg m^{-3}. Interesting to note is that in some areas with high WUE, the WUE remains similar from year to year, e.g. southeast and eastern corner (enlarged), suggesting that these farms are applying best management practices to ensure consistently high WUE.

In the Worcester area, the WUE of wine grapes increased slightly and that of table grapes decreased from 2004-5 to 2005-6 (Table 3). Figure 12 shows a year to year and spatial variation in WUE, with the WUE increasing in some areas whilst decreasing in other areas. Note that grapes produced in the northern part of Worcester generally have a lower WUE compared to the grapes produced in the southern part (especially the south eastern area closer to the Bergriver) of Worcester. Also, compare the top and bottom left areas of Worcester where an increase in WUE, from 2004-5 to 2005-6, is clear. In contrast, the WUE of grapes in some areas decreased from 2004-5 to 2005-6 (e.g. eastern area of Worcester).

In Paarl farmers generally aim at producing good quality wine (often of a smaller quantity) whereas in the Worcester area, the aim is generally to produce great quantities of wine grapes, mainly utilized in the production of brandy. These different framing strategies area reflected in the spatial representation of WUE for these two areas (Figure 13). The WUE in Paarl is higher than in the Worcester area. In some areas of Paarl, WUE of up to 7 kg m^{-3} are achieved showing that water in these areas is utilized very efficiently in the production of wine grapes.

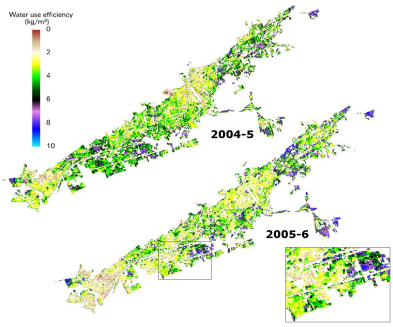

Figure 11 Water use efficiency of table grapes in the Hexriver valley based on SEBAL total evaporation and biomass estimates for the growing seasons of 2004-5 and 2005-6. Highly productive areas are consistent between the two seasons of study.

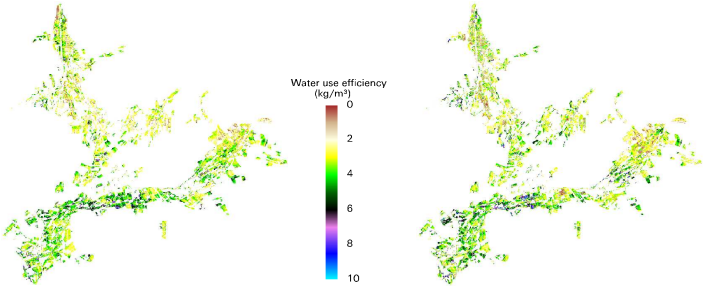

Figure 12 Water use efficiency of table grapes in the Worcester area based on SEBAL total evaporation and biomass estimates for the growing seasons of 2004-5 and 2005-6. Highly productive areas are consistent between the two seasons of study.

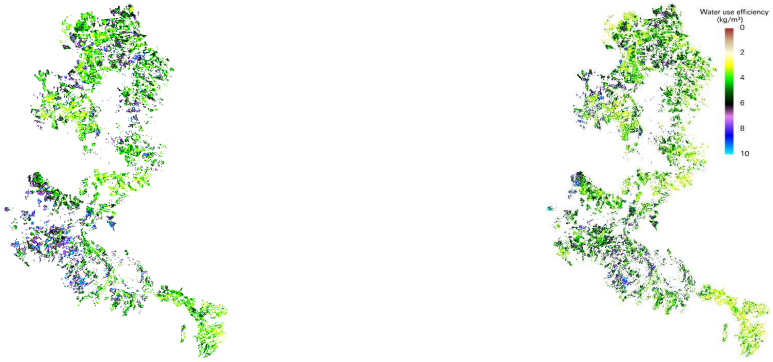

Figure 13 Water use efficiency of table grapes in the Paarl and Franschhoek areas based on SEBAL total evaporation and biomass estimates for the growing seasons of 2004-5 and 2005-6. Highly productive areas are consistent between the two seasons of study.

3.5.1 International estimates of WUE

The water use efficiencies of table and wine grapes in the four study areas in Western Cape are relatively high compared to water use efficiencies found in literature, indicating water is managed relatively well. The WUE is directly related to the yield production which is estimated from yield functions derived from limited data sets. Few examples in the literature exist for WUE of grapes where WUE is defined as the ratio between yield and actually consumed water. De Castro Texeira et al. (submitted) found water use efficiencies of 0.96-1.16 kg m^{-3} for wine grapes and 3.18 kg $m^{-3}$for young table grapes in Brazil. Yunusa et al. (1997a) determined seasonal WUE for own-rooted and grafted Sultana grapevines in Australia. WUE ranged between 2.58 up to 9.02 kg m^{-3}. Yunusa et al. (1997b) measured WUE of furrow-irrigated Sultana grapevines in south-eastern Australia. WUE ranged between 1.33 and 4.05 kg m^{-3}.

Walker et al. (2004) defined a transpiration efficiency, as the amount of biomass produced per unit of water that is actually transpired by the vine. The transpiration efficiency is expected to be slightly higher than the water use efficiency, as evaporation is not taken into account. Walker et al. (2004) found transpiration efficiencies of wine grapes (Shiraz and Cabernet) produced in Australia to range from 2.5 to 3.3 kg m^{-3} under well-watered conditions, and 2.0 to 5.1 kg m^{-3} under mild water deficit.

4. Conclusions

SEBAL accurately estimates total evaporation and yield of table and wine grapes in the Western Cape. Total evaporation is estimated to within 18 % of that measured, and yield to within 5 %. WUE of table grapes are generally lower than that of wine grapes, due to significantly higher ET of table grapes. WUE was on average 3.8 and 4.7 kg m^{-3} for table and wine grapes respectively. The considerable spatial variation in WUE in the grape producing areas, suggest that WUE can be improved. Spatial estimates of WUE can be used to evaluate differences in management practices and suggest improvements.

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References

Allen, R.G., Tasumi, M., Morse, A. and Trezza, R. 2005. A Landsat-based energy balance and total evaporation model in Western US water rights regulation and planning, Irrigation and Drainage Systems 19: 251-268

Allen, R.G., Tasumi, M. and Trezza, R. 2007. Satellite-based energy balance for mapping total evaporation with internalized calibration (METRIC) – Model. ASCE J. Irrigation and Drainage Engineering (in press).

Bastiaanssen, W.G.M., Ahmad, M.D. and Chemin, Y. 2002. Satellite surveillance of evaporative depletion across the Indus Basin, Water Resources Research, vol. 38, no. 12: 1273-1282.

Bastiaanssen, W.G.M., Noordman, E.J.M., Pelgrum, H., Davids, G., Thoreson, B.P. and Allen, R.G. 2005. SEBAL for spatially distributed ET under actual management and growing conditions, ASCE J. of Irrigation and Drainage Engineering 131(1): 85-93.

De Castro Texeira, A.H., Bastiaanssen, W.G.M., and Bassoi, L.H. Submitted. Crop water parameters of irrigated wine and table grapes in the Sao Francisco river basin, Brazil.

National Water Act of South Africa. 1998. Act 36 of 1998. Department of Water Affairs and Forestry.

Netzer, Y., Yao, C., Shenker, M., Cohen, S., Bravdo, B. and Schwartz, A. 2005. Water consumption of superior grapevines grown in a semiarid region. ISHS Acta Horticulturae 689: VII International symposium on Grapevine Physiology and Biotechnology.

Roux, A. 2006. Increase in water use efficiency: 1 Western Cape Province, South Africa. 3rd Asian Regional Conference, 13-15 September 2006, Kuala Lumpur, Malaysia.

Trambouze, W., Bertuzzi, P. and Voltz, M. 1998) Comparison of methods for estimating actual total evaporation in a row-cropped vineyard. Agric Forest Meteorol 91: 193-208

Voogt, M.P. 2006. MeteoLook, a physically based regional distribution model for measured meteorological variables. M.Sc. thesis, Technical University of Delft, Delft.

Walker, R., Gibberd, M., Stevens, R. and Pech, J. 2004. Application of carbon isotopic discrimination technology to understanding and managing wine grape water use efficiency. Final report to Grape and Wine Research and Development Corporation. Project Number CRV99/10.

Williams, L.E., Phene, C.J., Grimes, D.W. and Trout, T.J. 2003b. Water use of mature Thompson Seedless grapevines in California. Irrig Sci 22: 11-18.

Yunusa, I.A.M., Walker, R.R. and Blackmore, D.H. 1997a. Characterization of water use by Sultana grapevines (Vitis vinifera L.) on their own roots or on Ramsey rootstock drip-irrigated with water of different salinities. Irrig. Sci. 17: 77-86.

Yunusa, I.A.M., Walker, R.R. and Guy, J.R. 1997b. Partitioning of seasonal total evaporation from a commercial furrow-irrigated Sultana vineyard. Irr.Sci. 18: 45-54.

Zwart, S.J. and Bastiaanssen, W.G.M. 2007. SEBAL for detecting spatial variation of water productivity and scope for improvement in eight irrigated wheat systems. Agric Water Manage 89, 287-296.