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Windbreaks as part of climate-smart landscapes reduce evapotranspiration in vineyards, Western Cape Province, South Africa

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Abstract: Under the conditions of climate change in South Africa, ecological and technical measures are needed to reduce the water consumption of irrigated crops. Windbreak hedges are long-rated systems in agriculture that significantly reduce wind speed. Their possibilities to reduce evapotranspiration and water demand are being investigated at a vineyard in the Western Cape Province, South Africa. Detailed measurements of meteorological parameters relevant for the computation of reference and crop-specific evapotranspiration following the FAO 56 approaches within a vineyard in the Western Cape Province of South Africa have shown the beneficial effect of an existing hedgerow consisting of 6 m high poplars (*Populus simonii* (Carrière) Wesm.). With reference to a control station in the open field, the mean wind speed in a position about 18 m from the hedgerow at canopy level (2 m) was reduced by 27.6% over the entire year and by 39.2% over the summer growing season. This effect leads to a parallel reduction of reference evapotranspiration of 15.5% during the whole year and of 18.4% over the growing season. When applying empirical crop-specific K_c values for well-irrigated grapes, the reduction of evapotranspiration is 18.8% over the summer growth period. The introduced tree shelterbelts are a suitable eco-engineering approach to reduce water consumption and to enhance water saving in vineyards.

Keywords: *Vitis vinifera* L.; dry areas; viticulture; climate change mitigation; agroforestry; irrigation

With increasing population and agricultural production, water and land will become precious resources in South Africa. Already, large areas in South Africa are under intensive cultivation, providing an important quantity of food for South Africa and agricultural products for the world market. Consequently, more and more agricultural fields are converted into highly productive agricultural production systems. Therefore, agricultural production is also extended into the dry areas in the northern part of the Western Cape Province. Presently, there is a remarkable shift from grain production to grapes in the Swartland area (Halpern and Meadow 2013) and an extension of irrigated grapevine production into the Little Karoo region and along the Orange river. As Southern Africa is a water-scarce region challenged by substantial biophysical and socio-economic issues in agricultural

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production, fluctuations in rainfall are particularly relevant for agricultural production. Another important climatic parameter, which affects evapotranspiration and soil erosion, is the high wind speed along the coastal regions of the Western Cape Province (mean annual wind speed is 5–8 m/s at 10 m above ground in the cultivated areas of the Winelands area, and up to 20 m/s along the ridges; Western Cape Department of Agriculture 2016). Currently, after severe drought periods (Yuan et al. 2018), the reduction of crop water consumption is an important challenge for sustainable agriculture in Southern Africa (Mafongoya et al. 2018). Following the climate change predictions for Southern Africa, it is particularly the Western Cape that will become warmer (Fauchereau et al. 2003, Midgley et al. 2005, Christensen et al. 2007) with drastic implications for agricultural production and especially for intensive viticulture and horticulture (Benhin 2008, Araujo et al. 2016). Increased temperatures imply increased evaporation as a result of increased vapour pressure deficits. It has also been shown that the number of dry days between rainfall events has increased in the Western Cape (Carter 2006), and the changes in evaporation rates may reduce soil moisture and the availability of water resources in the long term. In the context of ongoing climate change and increasing population, there is an urgent need to optimize the water consumption of surface and groundwater in agricultural production in the Western Cape. Environmental friendly innovations are required to enhance the livelihood of farmers and to reduce negative environmental impacts. Climate-smart agricultural technological innovations at the farm level have the potential to address climate-related challenges (Senyolo et al. 2018). Meanwhile, various management approaches like drip-irrigation systems and the replacement of water source, and reuse of wastewater and lower water quality (Ben-Gal et al. 2008) were developed to minimize the usage of rain and groundwater resources.

A major approach to reduce water demands is eco-engineering measures influencing directly soil evaporation and crop transpiration. The redesign of the agricultural landscape by the introduction of specially designed obstacles to airflow will significantly influence the near-ground wind field. For centuries it is a well-known fact that the establishment of tree shelterbelts is an appropriate method to reduce wind speeds to minimize soil erosion and to enhance soil quality (Burel 1996, Cui et al. 2012). This applies especially to crops with high water demand, such as vineyards and fruit orchards (Sheridan et al. 2005). While the overall effect of shelterbelts is common knowledge, it is still not clear what the possible positive effects on crop production and water use efficiency maybe since only a few studies were conducted in agroforestry systems in Europe (Campi et al. 2009, Kanzler et al. 2019). It is generally accepted that agroforestry can provide various ecosystem services and can mitigate climate change effects (Hérnandez-Morcillo et al. 2018), but understanding the direct effects on microclimatic boundary conditions needs more detailed and process-oriented information about the interactions between trees and crops. Therefore, the approach of this study focusses on the effects of hedgerows on the field level and to provide a measure to support climate-resilient development planning on the farm and landscape level (Scherr et al. 2012). In a first step for the optimisation of the water use efficiency, we analysed the influence of a planted tree hedgerow within the vineyard on the reduction of near-ground wind speed and evapotranspiration.

MATERIAL AND METHODS

Site description. The study site is located in the Paarl wine district of the Cape Winelands (Meadows 2015) on the commercial vineyard Babylonstoren (Western Cape, South Africa; 33°49'27.69''S, 18°55'19.38''E, altitude 194 m a.s.l.). The climate in the Western Cape of South Africa is regarded as the Mediterranean, with wet winters and dry summers. In Paarl, the average annual rainfall is 770 mm, and in Stellenbosch 742 mm, respectively (Meadows 2015, CSAG 2016, Climate-Data.org). Most rainfall is in June, which has an average of 132 mm, while January is typically the driest month with an average of only 16 mm. In Paarl, the average yearly temperature is 17.6 °C, with February being the hottest month with an average temperature of 23 °C and July the coldest month with an average of 12 °C (Climate-Data.org). However, the temperature in Paarl during summer (Jan–Feb) regularly exceeds 30 °C. The Simonsberg vineyard area is characterised by granites, conglomerates, and loamy soils (Bargmann 2003). The clay content is < 15% with soil depth ≥ 450 mm and < 750 mm (Western Cape Department of Agriculture 2018). The poplar windbreak was planted in a single row with 1 m spacing and reached a height of 5 m.

Microclimatic measurement set-up. Microclimatic measurements were installed within a 4.2 ha trickle-irrigated vineyard with an NW-SE row orientation and a spacing of 2 m. The mast was located (*i*) 18 m north (hedge-station) of the existing poplar hedgerow (*Populus simonii* (Carrière) Wesm.) parallel to the vineyard rows and (*ii*) as a reference in approximately 100 m distance in the open field. Parameters measured are horizontal wind speed at 2 m and 6 m and wind direction at 6 m (RM Young Wind Sentry, USA), ambient temperature, and relative humidity (Vaisala HMP60, Vantaa, Finland), and precipitation (Texas Electronics Rain Gauge, USA) at 2 m. Global irradiation and albedo are measured directly above canopy level with an albedometer (Kipp and Zonen CMA11, Delft, the Netherlands). Heat-flux plates manufactured by Hukseflux (HFP01Sc, Delft, the Netherlands) were installed at 20 cm soil depth. All microclimatic data were sampled at 1 Hz and were recorded as 5 min averages by a data-logger (Campbell Scientific CR1000, Logan, USA). The data were transferred from the data-logger to a server at Stellenbosch University by GSM-data-modem. Data availability over the measurement period was 100% in all cases. The measurement period was April 2015 to March 2016 (12 months) and was sufficient for further data analysis and the generation of a statistical basis for small scale wind field modeling.

METHODOLOGY

There is a wide range of physical and empirical approaches to estimate actual evapotranspiration and crop-specific evapotranspiration (Novák 2012). Some are based on the radiative energy balance and the saturation deficit only, such as the original Penman and Penman-Monteith equations; others include water vapor and wind gradients above ground or a stand of crops such as the Thornthwaite-Holzman equation or focus on turbulent water vapor exchange above the crop canopy such as eddy covariance approaches (Littmann and Veste 2008). In an extensive overview, Allen et al. (1998) recommended the FAO combined Penman-Monteith approach as the sole method for determining reference evapotranspiration. In the FAO approach, the bulk surface and aerodynamic resistances r_s and r_a of the original Penman-Monteith equation (1):

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad (1)$$

are transformed into explicit terms of momentum (wind) and heat transfer (2):

$$r_a = \frac{\ln\left[\frac{z_m - d}{z_{om}}\right] \ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 u_z} \qquad (2)$$

where: r_a – aerodynamic resistance (s/m); z_m – height of wind measurements (m); z_h – height of humidity measurements (m); d – zero plane displacement height (m); z_{om} – roughness length governing momentum transfer (m); z_{oh} – roughness length governing transfer of heat and vapour (m); *k* – von Karman's constant, 0.41 (–); u_z – wind speed at height z (m/s), normally 2 m above ground.

$$r_s = \frac{r_I}{LAI_{active}}$$

where: r_s – (bulk) surface resistance (s/m); r_l – bulk stomatal resistance of the well-illuminated leaf (s/m); LAI_{active} – active (sunlit) leaf area index (m^2 (leaf area)/m^2 (soil surface)).

Reference values for irrigated crops are r_s = 70 s/m and r_a = 208/u_{2m} s/m (Allen et al. 1998). The resulting combined FAO Penman-Monteith equation (3) (Allen et al. 1998) provides an explicit tool to compute reference evapotranspiration values on different time scales (hour, day, month), depending on the measured input data resolution:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (3)$$

where: ET_o – evapotranspiration (mm/day); R_n – net radiation at the crop surface (MJ/m^2/day); G – soil heat flux density (MJ/m^2/day); T – air temperature at 2 m height (°C); u_2 – wind speed at 2 m height (m/s); e_s – saturation vapour pressure (kPa); e_a – actual vapour pressure (kPa); e_s – e_a – saturation vapour pressure deficit (kPa); Δ – slope vapour pressure curve (kPa/°C); γ – psychrometric constant (kPa/°C).

Estimates of crop-specific evapotranspiration over the crop growth period introduce the crop coefficient K_c which is used as a multiplication factor for reference ET_0 of the FAO Penman-Monteith equation. K_c depends on crop species, crop height, the albedo of the crop/soil surface, and on the total canopy resistance and is thus divided into the initial, mid, and late growing season. While $K_{c\ ini}$ and $K_{c\ late}$ may be derived from tabulated FAO values (Allen et al. 1998), $K_{c\ mid}$ should be computed following (4):

$$K_{cmid} = K_{cmid(Tab)} + [0.04(u_2 - 2) - \\ - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \qquad (4)$$

where: RH_{min} – 45% relative humidity; h – crop height (m).

As the Western Cape area is characterised by Mediterranean climate conditions, well-irrigated crops such as grapevine may show higher mid-season K_c values, as indicated in the FAO approach (Williams et al. 2003, Lazzara and Rana 2010). Therefore, we apply the following K_c values: initial growing season (October–November) 0.3, mid-season with continuous trickle irrigation (December to February) 1.0, and late season (March) 0.45. All computations were made based on daily mean measured values.

RESULTS

Effects on wind speed. During the observational period, April 2015 to March 2016, most frequent winds came from southern directions. Moreover, the typical bimodal seasonal wind regime over the area with southeasterly wind directions in summer and northwesterly airflow in winter was not pronounced over the measurement period as the prevailing wind direction measured was East-Southeast at both seasons. Under normal climatic conditions, the local wind regime in the area is characterised by southerly winds over the summer period when the Kalahari depression dominates the larger region, whereas during the winter period winds may prevail from northerly directions, especially when there is a higher frequency of cyclonic activity in the South Atlantic. Consequently, the winter period of 2016 showed a lower frequency of rain bringing cyclones (Western Cape Department of Agriculture 2016) and, consequently, a low frequency of northerly winds.

A generally weaker wind field is also shown in a comparison of long-term monthly wind speeds and wind speeds over the measurement period derived from MERRA 2 reanalysis data interpolated from a 0.5° × 0.5° grid for the study site at a height of 10 m above ground (NASA Langley Research Center 2020) shown in Table 1. While the measurement period was 4.2% below the long-term average, the summer season was 4.7% below, while the winter season was only 3.6% below the long-term average. Although the absolute MERRA 2 wind speeds cannot be directly compared to measured near-ground values, a computational downscaling of MERRA 2 wind speed from 10 m to 6 m above ground revealed the seasonal change of the power law's Hellmann exponent with values > 0.4 in the summer half-year and < 0.3 over the winter months when the grapevine is leafless and aerodynamic roughness is reduced.

Depending on the development of a strong thermal depression over the Kalahari Desert, the seasonal pattern at the study site generally showed higher mean wind speeds at 6 m above ground over the summer half-year (Figure 1). During the summer season (October to March), average wind speeds were 33.8% higher in the open field and 29.8% at the hedge (Table 2). Close to the canopy layer of the vineyard at 2 m measuring height (approx. 0.9 m above the canopy), the seasonal differences of wind speed are less pronounced. During summer, the average wind speed in the open field was 16.9% higher than in winter. The sheltering effect of the hedgerow was also apparent in the seasonal difference (Figure 1). Here, summer means wind speed was even lower than in winter (Table 2) because of the lee side position of the measurement relative to the prevailing wind directions. The overall difference in wind speed between the open field and the hedge was 6.4% at 6 m height and 27.6% at 2 m height, respectively. These differences were even more pronounced over the summer half-year, i.e., over the irrigation period and wind speed at the hedge in 2 m height was 39% lower as compared to the open field.

Standard deviations of wind speed show a similar pattern. While the annual averages are only slightly lower at the hedge position and winter half-year values are generally higher, implicating stronger fluctuations over the months with a higher porosity of the hedge,

Table 1. Mean monthly MERRA 2 wind speeds for the study site (10 m), and downscaled and measured wind speeds at 6 m above ground

	MERRA 2		Difference	MERRA 2 scaled to 6 m	Measured field 6 m
	1994–2019	2015–2016			
	(m/s)		(%)	(m/s)	
Apr	4.1	3.9	–3.9	3.1	2.7
May	3.8	3.6	–4.8	2.9	1.8
Jun	4.1	3.8	–6.1	3.3	2.0
Jul	3.9	3.9	–1.0	3.5	2.7
Aug	4.1	3.8	–6.9	3.4	2.5
Sep	4.1	4.2	1.3	3.7	3.1
Oct	4.4	4.0	–9.7	3.4	2.9
Nov	4.9	4.7	–3.9	3.7	3.2
Dec	5.0	4.2	–15.6	3.3	2.9
Jan	5.2	5.6	6.8	4.5	4.5
Feb	5.0	4.6	–8.4	3.6	3.1
Mar	4.5	4.6	2.4	3.6	3.2
Year	4.4	4.2	–4.2	3.5	2.9

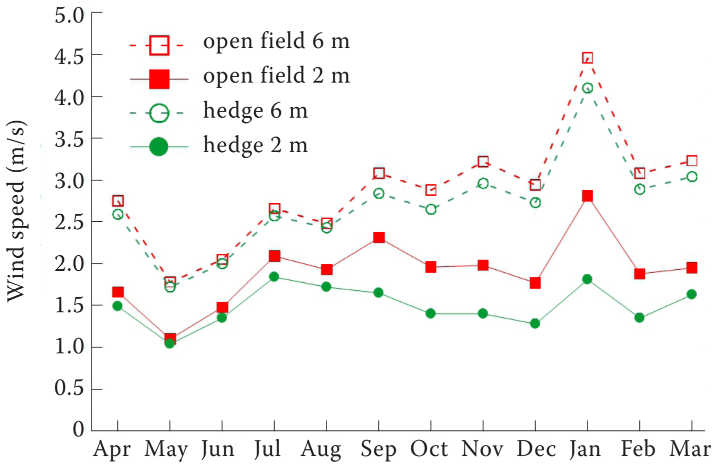

Figure 1. Monthly average of wind speed near the hedge (height 5 m) in a distance of 18 m north and in the open field and as a reference in approximately 100 m distance in the open field at Babylonstoren, Western Cape during the investigation period April 2015–March 2016. Predominantly southerly winds over the summer period

summer shows less fluctuations and the lowest values at the hedge at 2 m above ground (Table 2).

Seasonal variations of rainfall and evapotranspiration. Rainfall in the Winelands of the Western Cape primarily occurs during the winter season (Figure 2A). Over the measuring period, April 2015 to March 2016, the annual rainfall at the test site was only 511 mm, which was drastically below the long-term annual averages (Figure 2B) at the test site and in the Western Cape regions. The ET_0 values were computed as monthly mean values (Figure 2C) following the FAO 56 approach (Allen et al. 1998) based on daily averages of all relevant measured parameters. Annual evapotranspiration was 1 199 mm, while rainfall was 511 mm only, which implies a water balance deficit of 688 mm over the entire year. The calculation does not consider runoff and groundwater storage. Typical for a dry year with low winter rainfall, high rainfall intensities occurred almost exclusively over the summer half-year (singular maximum rainfall intensity was 63 mm/day). A comparison was performed for the calculated ET values (Figure 2B) based on long-term values generated for the Paarl area by a GIS-based mapping tool of Western Cape Department of Agriculture (Cape Farm Mapper, www.elsenburg.com), which indicated an average rainfall of 727 mm per year with annual reference evapotranspiration of about 1 270 mm. The calculated water deficit was only 543.5 mm compared to the 27% higher water balance deficit in 2015/2016, which resulted in higher water demand and crop irrigation.

The implication of the shelterbelt for evapotranspiration. The influence of the hedge on the reference ET_0 during the different seasons is shown in Figure 3. The hedge reduced the reference evapotranspiration by 18.4% over the summer irrigation season at the hedge position as compared to the open field situation and by 15.5% over the year, respectively. The positive effect is the lower calculated water deficit of 502 mm (annual ET_0 = 1 013 mm) compared to a deficit of 543.5 mm at the open field.

When applying the crop-specific K_c values for the early, mid, and late growing season of the grapes, we arrive at ET_c values about 33% lower than the annual ET_0 values and about 40% lower over the summer season (Figure 4). The reduction in crop evapotranspiration by the hedgerow is even slightly greater than the reduction in reference evapotranspiration during the summer growing season. Between October

Table 2. Seasonal averages for wind speed (m/s) at the Babylonstoren study site

Position/height of sensor		Winter (Apr–Sep)		Summer (Oct–Mar)		Year (Apr 2015–Mar 2016)	
		mean	stddev	mean	stddev	mean	stddev
Field	6 m	2.47	1.30	3.30	1.24	2.88	1.27
Hedge		2.36	1.21	3.06	1.11	2.71	1.16
Field	2 m	1.76	1.01	2.06	0.86	1.91	0.93
Hedge		1.52	0.82	1.48	0.48	1.50	0.65

stddev – standard deviation

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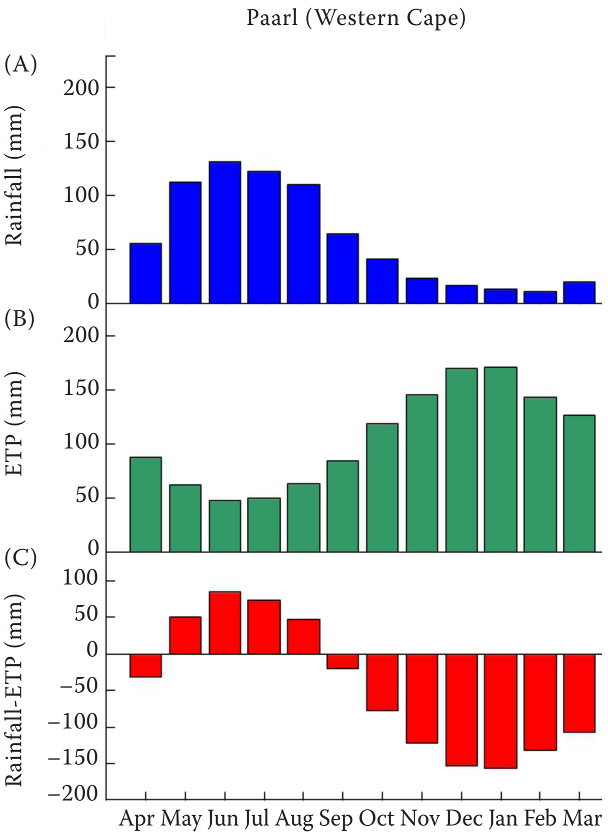

Figure 2. (A) Monthly mean rainfall; (B) evapotranspiration (ETP) and (C) water deficit (rainfall-ETP) at Paarl between April and March

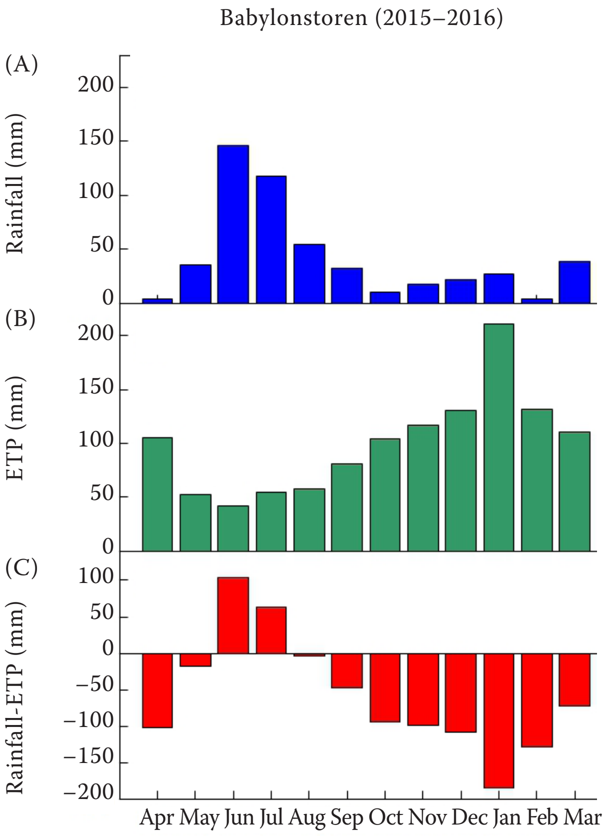

Figure 3. (A) Monthly rainfall; (B) evapotranspiration (ETP) and (C) water deficit (rainfall-ETP) at Babylonstoren between April 2015 and March 2016

and January, which is the main growing season, the reduction of crop evapotranspiration is between 18.4% and 20.4% compared to the reference site (Figure 5). In total, the water-saving by the integration of the hedgerow was 147.9 mm during the summer period and additionally 38.0 mm, which implies a reduction of the evapotranspiration of 15.1% over the year and of 18.9% over the summer irrigation season.

DISCUSSION

Our experimental results emphasised the importance of the introduction of tree shelterbelts to reduce wind speed in the Western Cape up to 39%. Wind speeds near the ground or near the crop canopy can be effectively reduced by flow obstacles, i.e., planted strips of vegetation as windbreaks and shelterbelts (Cleugh et al. 2002). Some explicit investigations have shown the reduction of wind speed on the downwind side of a shelterbelt as a function of distance, aerodynamic porosity, and height (Cleugh 1998, Foereid et al. 2002, Frank and Ruck 2005, Campi et al. 2009). Effective reductions of wind speed were measured within the distance of four to six times the height of the shelterbelt; minor reductions are effective up to 35 times the height (Wang and Tackle 1995, 1997). Our measured effects of the windbreak are in accordance with the literature with reductions of wind speed of 40% at a distance of 4.7 times of the hedgerow height (Marshall 1967, Cleugh and Hughes 2002). While distance to a shelterbelt is a parameter dependent on height and porosity, it has great significance for the planning of the width between two rows of shelterbelts in the field (Vigiak et al. 2003). Existing empirical approaches applying such parameterisation focus on the reduction of wind erosion but do not consider evapotranspiration (Fryrear et al. 1998, Böhm et al. 2014). The physical processes of evapotranspiration are mainly driven by the saturation deficit of the air depending on temperatures and the radiation balance, and the near-ground wind speed (Littmann and Veste 2008).

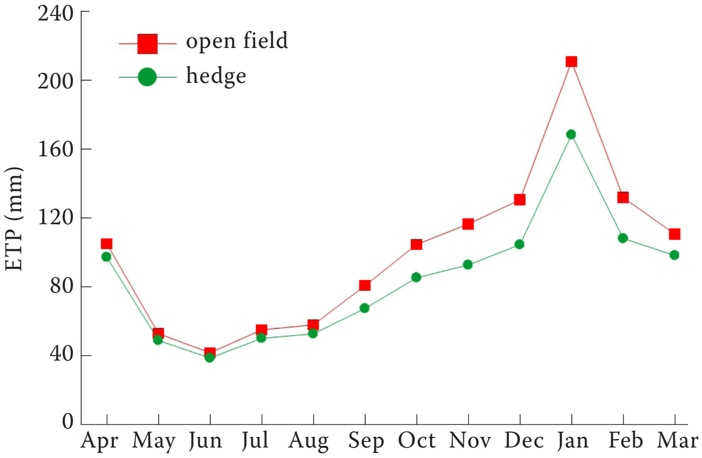

Figure 4. Monthly evapotranspiration (ETP) near the hedge (height 5 m) in a distance of 18 m north and the open field and as a reference in approximately 100 m distance in the open field at Babylonstoren, Western Cape during the investigation period April 2015–March 2016. Predominantly southerly winds over the summer period

Agro-engineering measures cannot directly influence the processes based on the saturation deficit of the air, but they can drastically reduce wind speeds. In a Spanish study area with a Mediterranean climate, the hedgerows modify boundary layer climates and had higher soil water content, lower wind speeds, and higher total soil organic matter (Sánchez and McCollin 2015). The evapotranspiration processes are also depending on the turbulent exchange and increase exponentially with wind speed over the canopy of a crop stand. ET is particularly important in environments with long hot, arid periods, such as the Mediterranean region, where a lack of water resources is the main factor limiting agricultural development. Campi et al. (2012) showed a remarkable reduction of the evapotranspiration up to 20% for durum wheat and 31% for beans for a low porosity barrier (20%). In our case, we observed a comparable reduction of the crop evaporation between 18.4% and 20.4% during the main growing season. There is a feedback between the reduced evaporation and crop water use efficiency, which can increase crop leaf area index and yields (Campi et al. 2009, Kanzler et al. 2019), which is triggered by improved microclimate conditions between the shelterbelts. Investigations by Lang et al. (2018) showed that agroforestry could improve water relations of grapevines. In that case study, leaf water potential and the corresponding available water reserves increased in the soil area for Riesling wine when cultivated in oak/poplar agroforestry systems, where Sauvignon Blanc wines are not influenced by the trees.

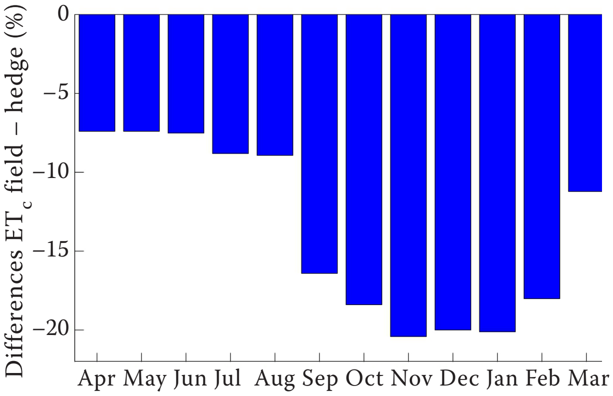

Figure 5. Monthly differences incrop-specific evapotranspiration (ET_c) between (*i*) near the hedge (height 5 m) in a distance of 18 m north and (*ii*) in the open field and as a reference in approximately 100 m distance in the open field at Babylonstoren, Western Cape between April 2015 and March 2016. Predominantly southerly winds over the summer period

However, the sustainable design of shelterbelts to improve microclimatic conditions and crop yields needs to take the local wind field conditions into account. Shelterbelts should reduce wind speed and evapotranspiration, but an increase in air temperature and overheating should be avoided. This is especially important in mountainous landscapes like the Winelands of the Western Cape. Sea breezes with the associated increase in wind speed in the afternoon and concomitant increase in relative humidity and reduction in temperature (Bonnardot et al. 2005) are of interest in the improvement of wine character and quality, and therefore it is from agro-economic relevance for the wine industry. Chemical composition and the related wine quality is not influenced by the interactions of grapevines and trees (Lang et al. 2018). Therefore, shelterbelt design should be modified to the specific local conditions and specific needs to ensure yields and wine quality, but also contributes to the needs for saving water in the wine industry. However, an appropriate selection of tree species for shelterbelt plantations is needed. In general, fast-growing trees have high annual biomass production, but also a higher water consumption (Veste and Böhm 2018). At present, information about tree water use of trees in agroforestry systems is rare. But the water consumption by the trees can be considerable. However, further detailed information about tree water use is needed to optimise the water use efficiency and ecohydrological implications of the combined to tree-grapevines systems or tree-crop interactions (Everson et al. 2011).

Our findings support the importance of the implementation of tree shelterbelt as a resource-preserving measure in viticulture in the Western Cape. The experimental results clearly showed that the integration of tree shelterbelts may reduce wind speed and evapotranspiration up to 20% within a range of about 5 times of the hedgerow height. This is a major implication for revisions of trickle irrigation control and planning of hedgerow plantings within the individual spatial pattern of fields at the farm level. However, these tree shelterbelts and hedgerows potentially reduce ETP to different extents with important implications for the ecosystem services that these systems provide in Mediterranean ecosystems. The integration of managed agroforestry systems, tree shelterbelt, and hedges into climate-smart agriculture can mitigate the effects of climate changes to a certain extent and improve the crop growth conditions.

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