INVESTIGATING THE POTENTIAL OF FIXED AND DRAPED NETTING TECHNOLOGY FOR INCREASING WATER PRODUCTIVITY AND WATER SAVINGS IN FULL BEARING APPLE ORCHARDS UNDER MICRO-IRRIGATION

Report to the
Water Research Commission

and

Hortgro Science

Edited by Stephanie J.E. Midgley[1,2], Sebinasi Dzikiti[1,3], Theresa Volschenk[4], Edward B. Lulane[1], Stephen C. Jordaan[1], Elmi Lötze[1], Zanele Ntshidi[3], Nompumelelo T. Mobe[3], Nicole J. Wagner[2]

[1]Department of Horticultural Science, Stellenbosch University
[2]Western Cape Department of Agriculture, Elsenburg
[3]Council for Scientific and Industrial Research, Smart Places Cluster, Stellenbosch
[4]Soil and Water Science Programme, ARC Infruitec-Nietvoorbij, Stellenbosch

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Obtainable from
Water Research Commission
Bloukrans Building, 2nd Floor
Lynnwood Bridge Office Park
4 Daventry Road
Lynnwood Manor
PRETORIA

orders@wrc.org.za or download from www.wrc.org.za

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EXECUTIVE SUMMARY

BACKGROUND

The installation of protective netting over fruit orchards is a promising adaptation response to stressful climatic conditions and climate change. Through reductions in direct radiation, air temperature and wind speed, and increases in air relative humidity, the microclimate under protective netting is milder. Daily and seasonal whole tree and orchard water use are potentially reduced. The extent of the response depends on changes occurring in the soil, in the tree (including regulation of transpiration through the stomata) and in the atmosphere under the net, compared to open trees. Thus, all aspects of the soil-plant-atmosphere continuum under netting must be better understood to guide the necessary adjustments in irrigation management.

Other significant benefits of netting include reductions in sunburn, wind damage and hail damage. The effects on yield, fruit size and other fruit quality parameters are variable according to the available literature and may depend on the regional climate, the type of netting, and the cultivar. The relationships between water use and fruit yield and quality (and thus water productivity) under nets are not well understood. Research on protective netting for apple (*Malus domestica* Borkh.) orchards in South Africa is limited and has not quantified the water-related benefits of production, quality and profitability at tree and orchard levels. Uptake of protective netting technology will be strengthened if multiple benefits and overall increased profitability over the orchard lifetime can be demonstrated. Since both fixed (covering the whole orchard) and draped (covering the tree row only) netting systems are currently available to farmers, research is needed to determine whether the water use and water savings differ between these systems.

RATIONALE

Increasing pressure on water resources in South Africa is a serious threat to the sustainability of the deciduous fruit industry. Water resources used by the industry for irrigation are coming under increasing strain due to: i) increasing competition from residential and industrial users; ii) the policy goals relating to greater equity of allocations; iii) the impacts of climate change with possible reductions in water supply to irrigation farmers, and; iv) the increase in demand of irrigated orchards under rising temperatures.

Water insecurity has been identified as a major risk by the deciduous fruit industry where production is totally reliant on irrigation. In turn, the importance of the deciduous fruit industry to national agricultural exports, foreign exchange earnings and employment cannot be underestimated. It is essential that the industry remains competitive and provides growth opportunities. This means that the water-related risks, but also the options to manage them, must receive attention through robust practical research, capacity building, and knowledge dissemination. Given the pressures in both supply and cost, growers will have to increase the water productivity of irrigated apple orchards. The use of protective netting over apple orchards is one of the promising emerging technologies that can be implemented.

AIMS AND OBJECTIVES

General aim

To compare water use of a high producing open and netted (fixed and draped) full bearing apple orchards under optimal management and unstressed water use conditions, in order to determine water savings per ha and per ton.

Specific objectives

1. To measure and model water use (expressed as evapotranspiration (ET)) of open and netted (fixed and draped) full bearing apple orchards under micro-irrigation.
2. To determine apple yield and quality of open and netted (fixed and draped) full bearing apple orchards.
3. To quantify water use efficiency and water productivity per ha and per ton of open and netted (fixed and draped) full bearing apple orchards.
4. To quantify water savings per ha and ton with micro-irrigation of netted (fixed and draped) full bearing apple orchards.
5. To explain the components of reduction of water use through transpiration and evaporation.
6. To budget and evaluate the reduction of water costs and increase of income from apple production, in comparison with the increased capital and maintenance costs of fixed and draped netting discounted over time.

METHODOLOGY

The study was conducted in the Koue Bokkeveld (KBV) and Elgin-Grabouw-Vyeboom-Villiersdorp (EGVV) production regions in the Western Cape, South Africa. Both regions have a Mediterranean-type climate with high levels of solar radiation in the growing season. The cultivars studied were ‘Rosy Glow’ (a high-coloured spontaneous single-limb mutation of ‘Cripps Pink’), ‘Golden Delicious’, and ‘Golden Delicious Reinders’®, a mutant of ‘Golden Delicious’. High-colouring red and bi-colour apple cultivars are seen to be financially viable under costly fixed netting systems, but are prone to poor colour development in lower light conditions. Green and yellow cultivars are sensitive to sunburn damage and changes in peel pigmentation. Draped netting is regarded as a better option for less profitable, but widely grown cultivars, in existing orchards.

Data were collected over three growing seasons, 2018-2019, 2019-2020 and 2020-2021. Three trials were conducted, as summarised in Table I. All orchards were high-yielding with good fruit quality. In the ‘Rosy Glow’ orchard, a white 20% knitted netting was installed in 2014 above the trees (4 m) in one section of the orchard, which was split into a control and a netted section. A fixed (permanent) flat structure was used. The trial was conducted for two consecutive seasons. In ‘Golden Delicious’ and ‘Golden Delicious Reinders’®, black draped netting with a 24% shade factor was installed after final fruit thinning in early summer, and removed at harvest. All orchards were irrigated using a micro-sprinkler irrigation system, and the soils were predominantly sandy.

Two treatments were established: 1) an open control, and 2) a netted section. Four rows of trees were marked and trees in the central two rows were used for measurements. Ten single-tree replications were marked in these two rows. Sap flow (transpiration, T), soil water content, and the microclimate in each orchard were monitored from full bloom in October until full leaf drop in July of each season. Four trees were instrumented for sap flow monitoring using the Heat Ratio Method (HRM), two trees were instrumented with time domain reflectometer soil water content sensors, and water flow meters were used to record irrigation volumes. Automatic weather stations were installed in the orchard using calibrated sensors. Orchard evapotranspiration (ET) was estimated using the soil water balance approach, and modelled using an adapted version of the dual source Shuttleworth and Wallace model. Trees were harvested and yield, fruit maturity and fruit quality recorded. Quality control data, pack out percentages into classes, and prices obtained for each class were provided by the pack house for the first two trials. Other measurements included soil physical properties, cover crop transpiration, and orchard floor evaporation, shoot and fruit growth rates, leaf area index, leaf gas exchange, and leaf and stem water potential. Physical and economic water productivity were calculated from seasonal T, ET, yield and orchard income.

Finally, where the results allowed, the water use savings of these orchards under netting and in the open were quantified, and the components of reduction of water use through transpiration and evaporation estimated. A farm enterprise model was adapted and used to model the increased income from production under netting over the orchard's lifetime, taking into account the water savings and other benefits, as well as the increased costs discounted over time.

RESULTS AND DISCUSSION

Both types of netting altered the orchard microclimate, but to varying extents. Results under fixed netting are summarised in a recent publication by Lulane et al. (2022) entitled: "*Quantifying water saving benefits of fixed white protective netting in irrigated apple orchards under Mediterranean-type climate conditions in South Africa"* published in *Scientia Horticulturae*. Averaged over two seasons, the nets reduced daily total solar radiation by ~ 12%, wind speed by more than 36%, and reference evapotranspiration by ~ 12%. Seasonal T was ~ 11% lower under nets, while ET was only ~ 4% lower (Table II). The differences in air temperature and relative humidity between the two treatments were very small, likely because of the small size of the fixed netted area. While the lower transpiration rates under the nets were expected, and they mirrored the changes in the atmospheric evaporative demand, the small difference in ET between netted and open orchards was rather surprising. Given that microlysimeter measurements of soil evaporation showed significantly lower soil evaporation under the fixed nets, the small ET difference can only be explained by a much more active vegetation cover on the orchard floor under the nets than in the open. This result suggests that while the fixed nets reduced tree level water use rates, careful management of the orchard floor is essential to maximize the water saving benefits of fixed nets. There is a higher likelihood of more vigorous weed and cover crop growth under the fixed nets than in the open, possibly due to more favourable growth conditions, i.e. milder microclimate and relatively wetter soils. This observation is further supported by the performance of the modified Shuttleworth and Wallace model (Dzikiti et al., 2018) in which the transpiration component under both treatments was accurately predicted, but the model significantly under-estimated the orchard floor evaporation, and hence ET under the nets. Another confounding factor in this study could be the substantially higher irrigation levels that were applied under nets than the control treatment, creating a wetter micro-environment. However, the possibility of much more growth of weeds and cover crops under the fixed nets should be investigated in future studies as these tend to diminish the water saving benefits of the fixed nets. Based on transpiration measurements, the physical water productivity (kg of fruit per m^3 of water transpired) was 14-15% higher under the nets, while this benefit was much smaller (~ 1%) when calculated on an ET basis. The economic water productivity (Rand per m^3 of water transpired) ranged between 20 and 45%, while no meaningful treatment difference was found when the calculations were based on ET. Observations on yield and fruit quality under fixed nets confirmed findings from earlier studies.

Table I. Summary of the study sites used in the KBV and EGVV production regions from 2018-2021.

	Site 1: Fixed white netting	**Site 2: Black draped netting**	**Site 3: Black draped netting**
Study year	2018-2019; 2019-2020	2019-2020	2020-2021
Region	KBV	KBV	EGVV
Cultivar	Rosy Glow	Golden Delicious Reinders	Golden Delicious
Rootstock	MM.109/M.9	MM.109	M.793
Year of planting	2010	2009	1987
Tree spacing	3.5 x 1.25	4.0 x 1.75 m	4 m x 2 m
Tree density	2285 trees ha^{-1}	1428 trees ha^{-1}	1250 trees ha^{-1}
Orchard area	Control: 0.49 ha Net: 0.26 ha	2.95 ha Net: 4 rows	ca. 1 ha Net: 4 rows
Farm name	Paardekloof	Paardekloof	Southfield
GPS coordinates	33°16'4.91"S, 19°15'53.72"E	33°15'36.25"S, 19°15'54.25"E	33°58’16”S, 19°18’31”E
Separate irrigation blocks	Yes, since 2016	Yes, since 2019	No
Irrigation system	Micro-sprinkler	Micro-sprinkler	Micro-sprinkler
Soil	Deep sand, <2% stone	Deep sandy loam to loamy sand, <1.5% stone	Deep sandy loam, no stones
Net type	White 20% knitted	Black HDPE, mesh 6 mm x 1.8 mm, 24%	Black HDPE, mesh 6 mm x 1.8 mm, 24%
Period of netting	Permanent since 2014	27-11-2019 to 25-02-2020	17-12-2020 to 10-03-2021
Fruit thinning	Chemical and hand	Chemical and hand	None
Growth regulation	Regalis® x2 applications in October; Early summer pruning, Winter topping and pruning	Winter topping and pruning	Winter topping and pruning
Soil additions	Compost, mulch	None	No

The draped nets reduced the solar radiation within the tree canopies by an even larger proportion (30-35%), presumably because of the higher shade factor (~ 24%). The air temperature was on average 1-2°C cooler while the relative humidity remained 5-10% higher under the nets. The higher relative humidity can be explained by the poor air circulation under the nets and transpiration of water vapour from the trees which gets trapped under the nets. The effect of this was a decrease in the vapour pressure deficit of air under the nets by between 0.1 and 0.2 kPa which reduced the atmospheric evaporative demand. Transpiration declined by ~ 9% under the draped nets (Table II). This figure is an average over two seasons, but also from two different sites. The difference in water use based on ET data were mixed between the two seasons likely because of methodological limitations. It was difficult to accurately predict the deep drainage component in the soil water balance calculation which may explain some of the differences, especially given the very high irrigation levels in some orchards. With much more precise needs-driven irrigation practices (i.e. avoidance of over-irrigation and deep drainage) of drape netted orchards it is likely that changes in ET would support a greater water use savings. Yield was higher under the draped nets, varying between 6% (farm data, 2020, linked to smaller fruit size) and 14% (trial data, 2021, not significantly different) between the years and sites.

CONCLUSION

Protective netting installed over apple orchards in the Western Cape of South Africa has very clear benefits for production and marketable yield, and thus farm income, even when considering the costs of installation and maintenance. This study has confirmed that a saving in water use per hectare and per ton of fruit in high-yielding irrigated apple orchards is possible, adding to the other benefits of this technology. While the results were influenced by net type (fixed white, black draped), cultivars, tree age/size, production region, and season, a reduction in orchard level transpiration of between 3% and 15% was found under netting compared to the open control across three orchards. Orchard evapotranspiration differed more widely, between a reduction of 19% and an increase of 16%. Thus, absolute water savings varied. Physical water productivity (kg m^{-3}) based on transpiration was consistently increased (10-34%); but the values based on evapotranspiration ranged from no effect to a 30% increase. Economic water productivity (R m^{-3}) showed clear benefits of netting, with increases of 3-30% based on evapotranspiration.

Challenges with complex measurement techniques and other factors, such as optimised irrigation scheduling for the two treatments, lead us to conclude that these results should be regarded as an initial indication of potential water use savings under nets. The moderate savings achieved are likely partially explained by the microclimatic dynamics under the nets used. A relatively small area of fixed netting with open sides, and draped netting that only covers the canopy, result in no other changes in microclimate except a reduction in solar radiation and wind speed. Thus, evapotranspiration is not clearly reduced, especially where applied irrigation may be more than required. Very precise irrigation under nets is likely to yield greater water savings benefits. There was also some evidence to suggest that more vigorous growth of the cover crop under the fixed net contributed to a higher orchard evapotranspiration, and that a greater water savings may be achieved with adjusted cover crop management.

Table II. Summary of the seasonal water use of apple orchards in the three trials over three seasons, 2018-2019, 2019-2020 and 2020-2021. T represents orchard level transpiration, and ET represents the orchard evapotranspiration. Transpiration data was derived from sap flow measurements while ET was modelled using the Shuttleworth and Wallace model. Irrigation rates, yield, physical water productivity and economic water productivity are also presented. Water productivity was calculated on the basis of T and ET. Percentage differences between the control and net treatments are given.

	Site 1: Fixed white netting 'Rosy Glow' 2018-2019	**Site 1: Fixed white netting 'Rosy Glow' 2019-2020**	**Site 2: Black draped netting 'Golden Delicious Reinders' 2019-2020**	**Site 3: Black draped netting 'Golden Delicious' 2020-2021**
T (m^3 ha^{-1}) (Oct-May)	Open: 5 810 Net: 5 330 Difference: -8%	Open: 6429 Net: 5462 Difference: -15%	Open: 6168 Net: 5966 Difference: -3%	Open: 8121 Net: 6930 Difference: -15%
ET (m^3 ha^{-1}) (July-June)	n.a.	Open: 9919 Net: 9845 Difference: -1%	Open: 9819 Net: 7990 Difference: -19%	Open: 7121 Net: 8267 Difference: +16%
Irrigation (m^3 ha^{-1}) (Oct-May)		Open: 9 359 Net: 10 443 Difference: +12%	Open: 7511 Net: 6797 Difference: +9.5%	Open: 6006 Net: 6142 Difference: -2.3%
Yield (t ha^{-1})	Open: 132.3 Net: 138.7 Difference: +4.8%	Open: 113.5 Net: 110.6 Difference: -2.6%	Open: 142.7 Net: 151.5 Difference: +6.2%	Open: 102.1 Net: 116.5 Difference: +14.1%
Physical water productivity (kg m^{-3}) T-based	Open: 22.8 Net: 26.0 Difference: +14.3%	Open: 17.7 Net: 20.3 Difference: +14.7%	Open: 23.1 Net: 25.4 Difference: +9.7%	Open: 12.6 Net: 16.8 Difference: +33.7%
Economic water productivity (R m^{-3}) T-based	Open: 80.1 Net: 114.6 Difference: +43.2%	Open: 86.6 Net: 104.6 Difference: +20.8%	Open: 69.2 Net: 75.8 Difference: +9.6%	Open: 24.6 Net: 38.3 Difference: +55.5%
Physical water productivity (kg m^{-3}) ET-based	n.a.	Open: 11.4 Net: 11.2 Difference: -1.8%	Open: 14.5 Net: 19.0 Difference: +30.5%	Open: 14.3 Net: 14.1 Difference: -1.7%
Economic water productivity (R m^{-3}) ET-based	n.a.	Open: 56.1 Net: 58.0 Difference: +3.4%	Open: 43.4 Net: 56.6 Difference: +30.2%	Open: 28.1 Net: 32.1 Difference: +14.3%

ACHIEVEMENT OF AIM AND SPECIFIC OBJECTIVES AS SET OUT IN THE CONTRACT

The contract objectives have, to a large extent, been met and in some instances exceeded. Comprehensive data were collected which allowed the researchers to compare the water use of high producing open and netted (fixed and draped) full bearing apple orchards, in order to determine water savings per ha and per ton.

However, it was challenging to achieve optimal management of irrigation in the various orchards to ensure unstressed water use conditions. There were some instances of over- and under-irrigation owing to operational decisions made by farm and irrigation managers based on observations and experience in unnetted orchards, which affected evapotranspiration. This is discussed and recommendations for future research and for practice have been formulated.

A suitable model for estimating apple orchard water use was applied in this study, specifically for 'Rosy Glow' under fixed nets. The model can be used to extrapolate the results of this study to other apple growing regions, but would benefit from further refinement and testing. Modelling was not conducted for the draped netting trials.

The data sets are for the most part complete, but some gaps and challenges exist. In the first season, the data recorded for solar radiation and the input data required for estimating orchard evaporation were problematic. For the third season (draped net trial on 'Golden Delicious'), farm and packhouse data were not available. This precluded comparison of trial results (yield, quality) with whole orchard results, calculations of economic water productivity, and the budgeting of costs and income under draped netting compared to the open.

The research conducted by the MScAgric student added considerable depth to the understanding of sustainable production potential, and thus long-term benefits of netting for increased crop water productivity. The relevant objectives were thus exceeded. This study is presented in this report only as the thesis abstract, but will be available (in thesis format) and will yield one scientific article.

All deliverables were completed and submitted. Additional outputs included one published scientific article, two popular articles, and six presentations (including two at international symposia). Further scientific articles and one popular article are in the pipeline.

NEW KNOWLEDGE AND INNOVATION

This study has generated new knowledge regarding the efficacy of fixed and draped shade nets technologies which are increasingly being adopted by growers in South Africa and elsewhere. While the benefits of these technologies on tree growth, yield quality and quantity have been reported elsewhere, little information exists on their water saving benefits. This study also investigated the mechanisms by which the water saving benefits are achieved which is essential for the proper implementation of the technology. In the case of fixed nets, for example, new knowledge generated shows that water saving benefits are maximum early and late in the season and this trend is influenced by the size of the area under nets. The differences in both the microclimate and tree water use are smallest in the peak summer season in small netted areas due to the active mixing of air from outside and under the nets. To achieve maximum benefits from fixed nets in terms of water savings, the size of the netted area matters. Other new information with significant implications on orchard management is that fixed nets appear to be associated with more active ground cover. This may reduce the water savings derived from lower tree transpiration rates, so careful orchard floor management is critical.

CAPACITY BUILDING

Two postgraduate students were registered on this project. Mr Edward Lulane (PhDAgric in Horticultural Science, Stellenbosch University) will be submitting his thesis entitled “Quantifying the water productivity and water savings of apple orchards under fixed and draped netting” within the next two months. Mr Stephen Jordaan (MScAgric in Horticultural Science, Stellenbosch University) will graduate in March 2023.

As part of non-degree capacity building, Ms Nicole Wagner (Western Cape Department of Agriculture) contributed to the component “Budget and evaluate the reduction of water costs and increase of income from apple production, in comparison with the increased capital and maintenance costs of fixed and draped netting”.

Capacity building took place at the three collaborating institutions: Stellenbosch University, Council for Scientific and Industrial Development, and Agricultural Research Council. Researchers improved their skills in several measurement techniques. Research managers at Hortgro Science will benefit from the availability of good science-based data on water use under nets that can be disseminated in the industry using Hortgro's various communication platforms.

The results of the research were shared with other researchers (both locally and internationally), industry technical advisors, the Hortgro Irrigation and Nutrition Workgroup, and the broader base of pome fruit farmers, through an industry research showcase and regional seminar. Project outputs include one scientific publication in *Scientia Horticulturae*, two popular articles in the *South African Fruit Journal*, and several oral presentations.

Once the summary of the project and practical guidelines are available and disseminated, growers can take advantage of the understanding and technical options to implement appropriate practices. The project will improve the capacity of technical advisors to provide science-based guidance to growers regarding practices under shade nettings and especially irrigation management and scheduling.

CONCLUSIONS

Protective netting installed over apple orchards in the Western Cape of South Africa has very clear benefits for production and marketable yield, and thus farm income, even when considering the costs of installation and maintenance. This study has confirmed that a saving in water use per hectare and per ton of fruit in high-yielding irrigated apple orchards is possible, adding to the other benefits of this technology. While the results were influenced by net type (fixed white, black draped), cultivars, tree age/size, production region, and season, a reduction in orchard level transpiration (T) of between 3% and 15% was found under netting compared to the open control across three orchards. Orchard evapotranspiration differed more widely, between a reduction of 19% and an increase of 16%. Thus, absolute water savings varied. Physical water productivity (kg m^{-3}) based on transpiration was consistently increased (10-34%); but the values based on evapotranspiration ranged from no effect to a 30% increase. Economic water productivity (R m^{-3}) showed significantly greater benefits of netting. Challenges with complex measurement techniques and other factors such as optimised irrigation scheduling for the two treatments lead us to conclude that these results should be regarded as an initial indication of potential water use savings under nets. The moderate savings achieved are likely explained by the microclimatic dynamics under the nets used. A relatively small area of fixed netting with open sides, and draped netting that only covers the canopy, result in no other changes in microclimate except a reduction in solar radiation and wind speed. Thus, evapotranspiration is not clearly reduced, especially where applied irrigation may be more than required. Very precise irrigation under nets, and a change to closed sides in fixed netting systems, may yield greater water savings benefits.

RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the results of this study, the following recommendations can be made:

1) Orchard size seems to influence the microclimate and hence the water savings under fixed nets. This idea needs to be investigated further to make recommendations on the minimum fixed nets size required to achieve significant water savings.

2) Do fixed nets indeed promote more active ground cover? If so, what are the implications on water savings from this type of net?

3) This study only investigated the effects of fixed and draped nets on two apple cultivars namely 'Golden Delicious'/'Golden Delicious Reinders' and 'Rosy Glow'. How effective is this technology on other cultivars?

4) What are the effects of closing the sides of a fixed net in terms of microclimate, water savings and fruit quality?

5) Canopy microclimate varies from tree to tree and between orchards over short distances. This means that careful experimental layout is critical for comparative studies. Trees used for the treatments should be as similar as possible at the start, and automatic weather stations should be placed carefully within each treatment.

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LIST OF ABBREVIATIONS

A	Net CO_2 assimilation rate
ANOVA	Analysis of Variance
ARC	Agricultural Research Council
AWS	Automatic Weather Station
CO_2	Carbon Dioxide
CRY	Cryptochrome
CSIR	Council for Scientific and Industrial Research
CWR	Crop Water Requirement
DAFF	Department of Agriculture Forestry and Fisheries
DEA	Department of Environmental Affairs
DUL	Drained Upper Limit
E	Leaf transpiration rate
EGVV	Elgin/Grabouw/Villiersdorp/Vyeboom
ET_o	Reference evapotranspiration
FAO56	Food and Agriculture Organization, paper no 56
FC	Field Capacity
FIPAR	Fractional Interception of Photosynthetically Active Radiation
FR	Far Red
GDP	Gross Domestic Product
GMT	Greenwich Mean Time
g_s	Stomatal Conductance
H_2O	Water
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
IRGA	Infrared Gas Analyser
KBV	Koue Bokkeveld
Kc	Crop Coefficient
Kcb	Basal Crop Coefficient
LAI	Leaf Area Index
LAIc	Cover Crop Leaf Area Index
LED	Light Emitted Diode
LSD	Least Significant Difference

LWD	Leaf Wetness Duration
MAD	Mean Absolute Difference
MAE	Mean Absolute Error
MDS	Maximum Daily Shrinkage
MxD	Maximum Difference
NIR	Near Infrared
NSE	Nash-Sutcliffe Efficiency
NWRS	National Water Resource Strategy
PAR	Photosynthetically Active Radiation
Pb	Soil Bulk Density
PPFD	Photosynthetic Photon Flux Density
PVC	Polyvinyl Chloride
PWP	Permanent Wilting Point
R(i)	Radiation interception
RBD	Reproductive Bud Development
REW	Readily Evaporable Water
RH	Relative Humidity
RHFA	Relative Homogeneous Farming Area
RMSE	Root Mean Square Error
SAI	Sapwood Area Index
SAWS	South African Weather Service
SE	Standard Error
SH	Southern Hemisphere
SW	Shuttleworth and Wallace
SWB	Soil Water Balance
SWC	Soil Water Content
T_{leaf}	Leaf surface temperature
TCs	Thermocouples
TDP	Thermal Dissipation Probe
TEW	Total Evaporable Water
TSS	Total Soluble Solids
UKZN	University of KwaZulu-Natal
USA	United States of America

UV	Ultraviolet
VPD	Vapour Pressure Deficit
VPD_{leaf}	Leaf-to-air vapour pressure deficit
WC	Water Content
WCG	Western Cape Government
WP	Permanent Wilting Point/ Water Productivity
WPe	Economic Water Productivity
WPp	Physical Water Productivity
WRC	Water Research Commission
WUE	Water Use Efficiency
WUE_{inst}	Instantaneous Water Use Efficiency
WUE_{intr}	Intrinsic Water Use Efficiency
WUT	Water Use per Ton of fruit

LIST OF SYMBOLS

A	Leaf area (m^2)
e_a	Actual vapour pressure of the air (kPa)
e_s	Saturation vapour pressure of the air (kPa)
e_0	Actual vapour pressure of the air (kPa)
E_s	Soil evaporation (mm h^{-1})
ET	Actual evapotranspiration (mm h^{-1})
ET_o	Reference evapotranspiration (mm d^{-1})
f_c	Fraction of the ground surface covered by vegetation at midday
F_r	Stomatal sensitivity adjustment factor (0-1)
$f\theta$	Stress factor for soil moisture
Fs	Sap flux density (cm^3 cm^{-2} d^{-1})
h	Tree height (m)
K	Extinction coefficient (-)
K_c	Crop coefficient (-)
K_d	Density coefficient (-)
K_{cb}	Basal crop coefficient (-)
LAI_c	Leaf area index of the cover crop (-)
NSE	Nash-Sutcliffe Efficiency
θ_{FC}	Volumetric soil water content at field capacity (cm^3 cm^{-3})
θ_{WP}	Volumetric soil water content at permanent wilting point (cm^3 cm^{-3})
Pa	Atmospheric pressure (kPa)
R^2	Coefficient of determination
r_a	Average stomatal resistance (s m^{-1})
r_b	Aerodynamic resistance (s m^{-1})
RMSE	Root means square of error
SWC	Soil water content (cm^3 cm^{-3})
U_z	Wind speed at 2.0 m (m s^{-1})
RH_{max}	Maximum relative humidity (%)
RH_{min}	Minimum relative humidity (%)
R_n	Net radiation (MJ $m^{-2}d^{-1}$)
R_{nc}	Net radiation at tree canopy (MJ $m^{-2}d^{-1}$)
R_{ng}	Net radiation on orchard floor (MJ $m^{-2}d^{-1}$)

R_{ns}	Net radiation at soil surface (MJ $m^{-2}d^{-1}$)
R_s	Solar radiation (MJ $m^{-2}d^{-1}$)
SAI	Sapwood area index (m^2 m^{-2})
SF	Sap flow (cm^3 h^{-1})
T	Transpiration (mm h^{-1})
T_a	Average air temperature (˚C)
T_c	Cover crop transpiration (mm h^{-1})
T_{min}	Minimum air temperature (˚C)
T_{max}	Maximum air temperature (˚C)
U	Sap flux density (cm^3 cm^{-2} d^{-1})
U_2	Mean wind speed (m s^{-1})
Vh	Heat pulse velocity (cm h^{-1})
VPD	Vapour pressure deficit of the air (kPa)
Z_e	Effective depth of soil evaporation (m)

LIST OF GREEK SYMBOLS

Δ	Slope of the saturation vapour pressure vs air temperature curve (kPa K^{-1})
γ	Psychrometric constant (kPa K^{-1})
σ	Stefan-Boltzmann constant (MJ $K^{-4}m^{-2}d^{-1}$)
α	Canopy resistance parameter (s m^{-1})
θ	Volumetric soil water content (m^3 m^{-3})
ε_a	Emissivity of the air (-)
ε_s	Emissivity of the surface (-)
Ψ_{em}	Early morning leaf water potential (MPa)
Ψ_{leaf}	Leaf water potential (unenclosed) (MPa)
Ψ_{stem}	Midday stem water potential (MPa)
Ψ_{pd}	Pre-dawn leaf water potential (MPa)
ψ_x	Xylem water potential (MPa)
$\boldsymbol{\lambda}$	Latent heat of vaporization (J kg^{-1})

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The installation of protective netting over fruit orchards is a promising adaptation response to stressful climatic conditions and climate change. Through reductions in direct radiation, air temperature and wind speed, and increases in air relative humidity, the microclimate under protective netting is milder (Middleton and McWaters, 2002; Solomakhin and Blanke, 2010a). This can often increase stomatal conductance and net CO_2 assimilation rates, but the lower vapour pressure deficit between the leaf and the air (VPD_{leaf}) can lead to lower transpirational water loss (Gindaba and Wand, 2007 a,b). Consequently, whole tree and orchard water use is potentially reduced (Middleton and McWaters, 2002). This, however, depends on the vigour and total leaf area of trees which can increase under the atmospheric, soil temperature and soil moisture conditions prevalent under protective netting, compared to open trees.

Other significant benefits of netting include reductions in sunburn (Gindaba and Wand, 2005), wind and hail damage. The effects on yield, fruit size, red colour and sugars are variable according to the available literature (Mupambi et al., 2018). The relationships between water use and fruit yield and quality under nets are not well understood. Research on protective netting for apple (*Malus domestica* Borkh.) orchards in South Africa is limited (Smit, 2007; Smit et al., 2009; Gindaba and Wand, 2005, 2007 a,b) and has not quantified the water-related benefits of production, quality and profitability at tree and orchard level. Uptake of protective netting technology will be strengthened if multiple benefits and overall increased profitability over the orchard lifetime can be demonstrated. Since both fixed (covering the whole orchard) and draped (covering the tree row only) netting systems are currently available to farmers, research is needed to determine whether the water use and water savings differ between these systems.

A recent (2014-2018) WRC- and Hortgro Science-funded study (Project K5/2398//4) has determined the water use of high-yielding 'Cripps Pink' and 'Golden Delicious' orchards in the Koue Bokkeveld and Elgin-Grabouw-Vyeboom-Villiersdorp regions of the Western Cape (Dzikiti et al., 2018 a, b). In-depth measurements of both components of water use (transpiration and evaporation) and the development of a water use model have paved the way for further studies and application of the model to practical technologies such as netting which can assist with improved on-farm water management. This project intends to use these tools to investigate the potential water savings achievable in apples under shade netting (both fixed and draped netting systems) with micro-sprinkler irrigation, and to understand how these savings are achieved biophysically and biologically. Once these are understood, further technological or management improvements can be considered through further research.

Protective netting over orchards has been identified as an effective adaptation technology, but very little detailed scientific research is available to validate the expected benefits (water-related and otherwise) and to provide guidance to farmers and policy makers.

This study focuses on quantifying possible savings in fruit tree and orchard water use under protective netting compared to the open, and possible increases in crop water productivity in apples. We approach this from a microclimatological and physiological perspective at organ and whole tree level, as well as a whole orchard perspective.

1.2 RATIONALE

Increasing pressure on water resources in South Africa is a serious threat to the sustainability of the multi-billion Rand deciduous fruit industry. Water resources used by the industry for irrigation are coming under increasing strain due to: i) increasing competition from residential and industrial users; ii) the policy goals relating to greater equity of allocations to users denied access in the past, and to new farmers and agricultural development projects; iii) the impacts of climate change with possible reductions in water supply to irrigation farmers (particularly in the south-western Cape where reductions in rainfall are projected in addition to warming), and the increase in demand of irrigated orchards under rising temperatures (WCG, 2016; Midgley et al. 2021).

Water insecurity has been identified as a major risk by the deciduous fruit industry where production is totally reliant on irrigation. In turn, the importance of the deciduous fruit industry to national agricultural exports, foreign exchange earnings and employment cannot be underestimated. With a total annual turnover of R12.2 billion, and providing substantial job opportunities (Hortgro, 2021), it is essential that the industry remains competitive and provides growth opportunities. This means that the water-related risks must receive urgent attention, through robust research, capacity building and knowledge dissemination. Furthermore, based on past trends, the costs of applying irrigation water (as determined by electricity and water tariffs) will increase in future. Given the pressures in both supply and cost, farmers will have to increase the water productivity of irrigation.

In the broader South African context, the project is valuable for the following reasons:

1. **The results can inform farming and policy decision making:**

Farmers can consider the water-related benefits of using netting as part of the larger set of parameters used towards deciding on whether to install netting. This is potentially a particularly useful technological option to reduce water demand on water-stressed farms and in water-stressed catchments, whilst maintaining or even increasing production and income levels, but no detailed data yet exists to validate this. Farmers can also use the information to make decisions on how to adjust irrigation scheduling under netting to avoid over-irrigation with resulting production issues and wastage of scarce water resources.

The research can also support national government policy in the water sector (e.g. the Water for Growth and Development Framework 2030, and the National Water Resource Strategy (NWRS2, 2013)), and for adaptation to climate change (e.g. Climate Change Adaptation Strategy for Water (2016), Western Cape Climate Change Response Framework and Implementation Plan for the Agricultural Sector (2016)).

2. Development of new products for economic development:

Shade netting as a viable technology for deciduous fruit orchards is experiencing a phase of increasing uptake by farmers. Although the installation of netting is expensive, the economic benefits of mitigating numerous production risks have started to outweigh the costs, thus fuelling rising interest. The reduction in water use under netting has only recently become an additional selling point, especially given the recent severe drought, and the expectation of both more frequent water curtailments in future and increases in the cost of water supplied. Netting thus becomes an option for improved on-farm water management, while fruit quality and income can even increase. The local manufacture, supply and installation of netting systems will stimulate both small, medium and larger enterprises and create space for new entrants into the market, thus increasing competition and lowering costs. At the same time, irrigation system service providers will benefit from the results of this research by improving the quality of design and system operations under netting for optimal results.

3. Drive sustainable development solutions

Sustainable development is critically dependent on sustainable management of natural resources, such as water. Technologies which increase WUE and water productivity (WP) of intensively irrigated fruit orchards, such as shade netting, can deliver developmental benefits and help to drive job creation in the sector. Protective netting can potentially reduce operational costs and increase income, thus supporting employment opportunities for farm workers and others in the supply chain. The current drought has focused the sector on the need for water security and increased resilience to water shortages and increased orchard water demand as projected under climate change. One year of serious drought impacts on the trees can damage the entire future production potential of a 30-year investment. The apple industry must safeguard its reputation and ability to supply local and global markets reliably with good quality produce. Shade netting offers the amelioration and buffering of unacceptable variability in supply to the market.

4. Enhance human capital development

The project contributed significantly towards capacity building, through the training of MSc and PhD students. Other beneficiaries included the researchers, the technical staff at Hortgro Science, the collaborating farmers and their technical advisors, and the suppliers of shade netting systems.

5. Empower local communities

A sustainable and growing deciduous fruit industry, achieved through the benefits described above, will be able to preserve current jobs on farms and in the value chain, and provide opportunities for further job creation for local rural communities and new farmers. Opportunities could arise for the emergence of SMMEs to supply, install and maintain netting systems. The quality of local groundwater sources could improve since improved on-farm water management reduces the leaching of irrigation water out of the root zone. This benefits local groundwater-dependent communities and reduced health risks.

1.3 AIMS AND OBJECTIVES

1.3.1 General aim

To compare water use of a high producing open and netted (fixed and draped) full bearing apple orchards under optimal management and unstressed water use conditions, in order to determine water savings per ha and per ton.

1.3.2 Specific objectives

1. To measure and model water use (expressed as evapotranspiration (ET)) of open and netted (fixed and draped) full bearing apple orchards under micro-irrigation.
2. To determine apple yield and quality of open and netted (fixed and draped) full bearing apple orchards.
3. To quantify water use efficiency and water productivity per ha and per ton of open and netted (fixed and draped) full bearing apple orchards.

4. To quantify water use savings per ha and ton with micro-irrigation of netted (fixed and draped) full bearing apple orchards.
5. To explain the components of reduction of water use through transpiration and evaporation.
6. To budget and evaluate the reduction of water costs and increase of income from apple production, in comparison with the increased capital and maintenance costs of fixed and draped netting discounted over time.

1.4 APPROACH

The study was conducted over a period of four years, covering three full production seasons and four trials. The two treatments were in all the trials an open control orchard and an adjacent netted orchard, managed similarly in all other respects. The orchards were irrigated using micro-irrigation systems and the intention was to optimise irrigation in each treatment and avoid any over- or under-irrigation. Two types of netting were used: fixed flat white netting, and black draped netting.

In the first two seasons, a 'Rosy Glow' orchard under fixed netting in the Koue Bokkeveld region was used, with the same measurements conducted for two consecutive seasons. The first draped netting trial, using 'Golden Delicious Reinders', was conducted in the second season on the same farm as the fixed netting trial. In the third season, the second draped netting trial using 'Golden Delicious' was conducted in the Villiersdorp region. In all trials, data gathering commenced before full bloom (with a few exceptions) and continued to early winter. Results were analysed on a daily, monthly and seasonal basis.

In the last year, data analysis was completed, the students wrote their theses, and scientific and popular articles were written. This report serves as the integrated final project report and guidelines for the industry.

CHAPTER 2: KNOWLEDGE REVIEW

2.1 APPLE PRODUCTION AND IRRIGATION IN SOUTH AFRICA

2.1.1 Apple cultivars, rootstocks and production trends

The pome fruit industry of South Africa generates a turnover of approx. R 12.2 billion per annum (Hortgro, 2021). The apple industry is based on a planted area of 24 956 ha, generating approx. R 8.7 billion turnover, and providing substantial job opportunities. The most important production regions are Ceres (the Warm and Koue Bokkeveld), Groenland (better known as Elgin-Grabouw), Villiersdorp-Vyeboom and Langkloof. Approximately 80% of apple plantings are in the Western Cape Province.

Yields are on average about 60 t ha^{-1} across the apple industry, but very high-yielding orchards are achieving over 100 t ha^{-1} and in some cases >120 t ha^{-1}. A high quality of fruit is of the utmost importance, since 92% of pome fruit industry income is generated by fresh sales, and 46% of the crop is exported (Hortgro, 2021). Apples are exported primarily to Africa (29%), the Far East and Asia (28%), the United Kingdom (17%) and the Middle East (9%), with the important historical European market now only accounting for 7% of the exports.

The total production in South Africa is variable but has grown steadily, but with negative growth recorded in 2010, 2014, and 2016-2019 (Hortgro, 2021). The year-on-year decrease in marketable yields in these years was attributable to drought and hail events. Growth resumed strongly in 2020 and 2021, after the end of the multi-year drought.

'Golden Delicious' remains popular with consumers and continues to produce a high proportion of the total apple crop (20% of area planted). This is followed by 'Royal Gala'/'Gala' (17%) and 'Cripps Pink'/'Pink Lady®' and 'Granny Smith' (both 13%) (Hortgro, 2021). Fruit quality problems linked to high radiation and temperature in summer, such as sunburn, poor red colour development, pink blush on 'Granny Smith' and bleached green colour of green and yellow cultivars (Steyn et al., 2004; Makeredza et al., 2013; Gouws and Steyn, 2014; Hengari et al., 2014), are strong drivers of interest in improved cultivars and altered management practices. Soils in the Western Cape region are often shallow, stony, and nutrient-poor, which when combined with the climatic stresses, pose challenging conditions for fruit production.

2.1.2 Environmental factors influencing yield and fruit quality of apples

The deciduous fruit production potential is determined by local climate, ocean and mountain influences and soils, but is primarily limited by the need for cold winters and the availability of water.

2.1.2.1 Solar radiation

Solar radiation levels across South Africa are generally high owing to the latitudinal range of the country, and areas of high altitude. The coastal areas have a slightly lower solar radiation. In the apple production areas, radiation levels are lowest in the Elgin-Grabouw-Vyeboom-Villiersdorp (EGVV) (higher latitude, where partially cloudy conditions are also often experienced on summer days), followed by Langkloof (also higher latitude) and eastern Free State (frequent cloud cover), and highest in Koue Bokkeveld (KBV) which is at much higher altitude. Nevertheless, total radiation levels in South Africa are not limiting to photosynthesis of sun-exposed apple leaves, tree and fruit growth, and are in fact able to support high potential yields. The trade-off is that high radiation intensities result in a high prevalence of sunburn on apples in all the production areas (except the Free State where hail nets are used). Apple peel pigment synthesis and degradation, and thus visible green, yellow and red colour, are also highly sensitive to strong solar radiation.

While incoming photosynthetically active radiation is not limiting, adequate radiation interception and distribution in the orchard canopy for optimal carbon assimilation through photosynthesis, high yield and fruit quality is essential (Palmer, 1989; Wünsche and Lakso, 2000). The amount of radiation intercepted, and hence the actual yield, depends on various orchard design factors such as planting system, rootstock, tree spacing, tree shape, training system, row orientation and canopy management practices, e.g. pruning or the use of growth retardants that influence the leaf area index (leaf area per unit ground area), and the length of the growing season.

The relationship between apple yields and the total intercepted radiation shown in Figure 1 reveals a linear relationship up to about 50% radiation interception. Beyond the 50% interception, the relationship tends to be curvilinear and optimum apple yields are obtained at about 60 to 70% radiation interception according to Lakso (1994). In South African orchards, apple tree rows are usually planted in a north-south orientation to maximize radiation interception. Light distribution within canopies is increased by management practices such as pruning, spreading or tying down branches to a horizontal position.

The shift towards high density and more dwarfing plantings in South African orchards reflects a decrease in between-row and within-row spacings and increased orchard leaf area indices, which may increase radiation interception.

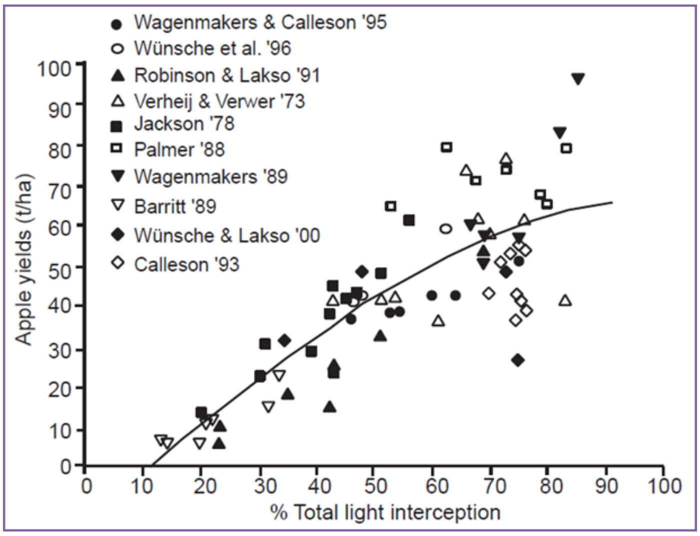

Figure 1 Summarized relationship between apple fruit yield and mid-season percent total orchard radiation interception from several reports in literature. Source: Lakso, 1994

2.1.2.2 Rainfall, temperature and evapotranspiration

The Mediterranean-type climate of the largest apple production region in South Africa, the Western Cape, is characterised by dry and warm to hot summers, and wet cool winters with some areas experiencing cold winters. There is, however, substantial climatic variability between the main apple-growing areas of KBV, EGVV and the Langkloof. The highest rainfall is experienced in EGVV, with annual rainfall reaching approx. 1000 mm in Elgin-Grabouw but dropping sharply to approx. 530

mm in Vyeboom-Villiersdorp. Significant water storage capacity in this mountainous area, in the form of both public and private dams, has allowed this area to expand irrigated agriculture, dominated by pome fruit orchards. The Langkloof has a slightly lower rainfall, with a greater proportion of the rain falling in the non-winter months. Private dams supply water for irrigation. The driest major production area is KBV, where private dams and groundwater are used to irrigate the orchards. The distinct rainfall seasonality and annual totals mean that almost the entire production area for apples is irrigated, since rainfall during the production season is, in most cases, negligible.

Apple production is concentrated in the cooler areas of the province where the criteria for apple production are best met, namely warm days in the growth season, and cool to cold nights in autumn and winter. The temperature regime of each production region is largely influenced by altitude combined with proximity to the ocean. The high-lying inland KBV area can experience higher daily maximum temperatures in mid-summer compared to the more coastal low-lying EGVV and Langkloof. The KBV benefits from a significantly colder winter season than EGVV and Langkloof, with sub-zero night time temperatures and snow not uncommon.

A critical environmental determinant of apple tree transpiration is the vapour pressure deficit of the air (VPD) and the difference between air VPD and VPD of the sub-stomatal cavity in the leaves (VPD_{leaf}). Since the relative humidity of the atmosphere on a summer day is fairly low in the winter rainfall production regions of South Africa, usually somewhere between 20% and 30% and occasionally measuring only 10-15%, it follows that VPD and VPD_{leaf} can be quite high on hot days. Values of > 3 kPa are commonly measured in orchards (Dzikiti et al., 2018a). Similarly, reference evapotranspiration (ET_o) is also commonly high during the middle of the day. These values are also increased by periods of strong prevailing winds during the growing season. In this study, ET_o is defined as evapotranspiration from a well-watered short grass reference surface which is healthy, actively growing and uniformly covering the ground according to Allen et al. (1998). This is calculated according to the modified Penman-Monteith equation.

Commercial apple production requires the accumulation of sufficient chill units, the cumulative number of hours below a specific temperature threshold during the dormant period from May until around August (Southern Hemisphere). Cultivar-specific thresholds of chill units are needed for satisfactory bud break, fruit set, yield and fruit quality. The chill units experienced in KBV are generally sufficient for most cultivars and the use of chemical rest-breaking agents to promote better bud break is usually not necessary for apple orchards. However, inadequate chill units are a significant problem in the warmer production areas such as EGVV (Cook and Jacobs, 2000).

2.1.2.3 Extreme weather events

The apple production regions of South Africa experience fairly regular extreme weather events. The Eastern Free State, for example, is prone to severe hailstorms, so that almost all apple orchards are covered with hail nets. The Langkloof is also fairly prone to hailstorms. Hail is uncommon in the Western Cape, but can occur on occasion, causing significant damage to crops in localised areas. In November 2013, hail damage wiped out crops (apple, pears, stone fruit and onions) on scores of farms in the Witzenberg, Ceres and Koue Bokkeveld areas and caused significant damage to much of the remaining crop. The predictability of the occurrence of hail is quite poor because of the dynamic and chaotic nature of the weather systems giving rise to hail.

Over the last 15 years, droughts have impacted the fruit industries in 2003-2004, 2010, and 2015-2018. The 2016-2019 apple harvests were significantly impacted through lower yields and fruit quality (Hortgro Science, 2018). Since commercial apple orchards are irrigated using mainly stored water, impacts generally arise during multi-year droughts when dam levels drop below critical thresholds. The relevance of installing protective netting in view of drought and the need to conserve scarce water resources is a central motivation for the compilation of this study. Other types of extreme weather events include storms with high wind speeds, extreme cold, and flooding following heavy rainfall. Strong winds can cause trees to lean over or even be uprooted, particularly for trees on dwarfing or semi-dwarfing rootstocks, and can damage or destroy infrastructure such as training systems and netting. The design of resilient protective netting systems must consider the local storm risks.

2.1.2.4 Soils

Apple trees can grow in a wide range of soils from medium textured clays to gravelly sands. However, poor soils will produce a poor crop. Preferred soil types are fertile sandy and loam soils having a pH in the range 5.5-6.5. Soils should be free from hard substrata and well drained. In most orchards the trees are planted on ridges to facilitate drainage. Poor aeration due to water logging increases the incidence of crown rot (*Phytophthora cactorum*), while too low or too high pH will affect the availability of nutrients to the trees. Soils in the major apple producing areas of South Africa are generally of a poor quality and lack uniformity (Voigt and Stassen, 2014). Orchard management practices, e.g. tree spacing and vigour management, are therefore adopted to maximise production, with an increasing tendency towards high density plantings.

2.1.2.5 Water resources

South Africa is a water scarce country. Surface water resources are almost completely allocated to various uses in most of the catchments containing intensive irrigated agriculture and growing towns and cities. Due to the rainfall seasonality in the winter rainfall region, fruit production is dependent on irrigation water and storage capacity is essential. Water for irrigation is provided by large public dams, private farm dams, and some rivers and their tributaries. Some regions such as KBV and Langkloof are reliant on local dams and sometimes groundwater. Water quality is a major risk which could worsen, impacting high value export crops. Further development of water resources will require the roll-out of significant wastewater treatment and re-use, a continued focus on water conservation and water demand management, increased water use efficiencies, greater use of groundwater (aquifers), reduction of water losses (leakages) through infrastructure repair and renewal, and possible desalination of saline ocean and ground water, the most expensive option.

Increasing pressure on water resources in South Africa is a serious risk to the sustainability and growth of the fruit industries. Water resources used by the industries for irrigation are coming under increasing strain due to: i) increasing competition from residential and industrial users; ii) the policy goals relating to greater equity of allocations to users denied access in the past, and to new farmers and agricultural development projects; iii) the impacts of climate change with possible reductions in water supply to irrigation farmers (particularly in the south-western Cape where reductions in rainfall and greater variability of rainfall are projected in addition to warming), and the increase in demand of irrigated orchards under rising temperatures and evapotranspiration (WCG, 2016). Furthermore, based on past trends, the costs of applying irrigation water (as determined by electricity and water tariffs) will increase in future. It is essential that the industry remains competitive and provides growth opportunities. This means that the water-related risks must receive urgent attention, through robust research, capacity building and knowledge dissemination.

The core objectives of national government policy in the water sector, e.g. the Water for Growth and Development Framework 2030, and the National Water Resource Strategy (NWRS2, 2013) is to ensure water for an equitable and sustainable future. Regarding future water needs in the agriculture sector, the NWRS2 states that a target of an increase of more than 50% of irrigated land in South Africa was set by the Irrigation Strategy of the Department of Agriculture, Forestry and Fisheries (DAFF). However, the NWRS2 points out that the Department of Water and Sanitation (DWS) assumes that the amount of water allocated for agriculture will remain the same and that an increase in irrigation will be achieved through increased WUE and selected new development. Recommended actions to increase agricultural WUE include, among others: 1) the need for accurate quantitative information on crop water use under different production practices, and 2) the adoption of precise irrigation technologies. Irrigation infrastructure in the South African apple industry is already modernized. Most fruit is produced under micro-sprinkler irrigation, with a smaller proportion irrigated using drip systems. In addition, the water saving practice of mulching is becoming the norm in the deciduous fruit industry. Further gains in WUE are being sought.

Additionally, the objective to increase water use efficiencies of agricultural production also responds to the need for climate change adaptation (e.g. Draft Climate Change Sector Plan for Agriculture, Forestry and Fisheries, 2013; Climate Change Adaptation and Mitigation Plan for Agriculture, Forestry and Fisheries, 2015; Climate Change Adaptation Strategy for Water, 2016; Western Cape Climate Change Response Framework and Implementation Plan for the Agricultural Sector, 2016; National Adaptation Strategy, 2020).

2.1.2.6 Climate change

Global climate change poses a significant threat to the agricultural sector. In South Africa, research on climate change risks and impacts continues but already indicates that agriculture in the Western Cape will be potentially severely affected (WCG, 2016; Midgley et al., 2021). Increases in temperature during the period 1931-2015 have been particularly high in the south-western Cape, rising by twice the global average rate of 0.1°C per decade at some stations. Further increases of between 1.5°C (closer to the coast) and 3°C (inland) are projected by mid-century across the country. A decrease in the number of rain days and in seasonal rainfall have been found in the south-western Cape during autumn. Modelled climate change projections indicate consistently a high likelihood of reductions in annual rainfall over the western parts of the Western Cape. Rainfall projections for the Langkloof and eastern Free State remain uncertain.

Apple production has been highlighted as being particularly vulnerable in the warmer production regions (especially EGVV) due to the reduction in chill units (Midgley and Lötze, 2011), but vulnerable in all regions to increasing heat stress and associated impacts on tree and fruit growth and fruit quality (WCG, 2016). In addition, warming will increase evapotranspiration (by ca. 5-15%) and the demand for irrigation (by ca. 8%, Schulze, 2016). Together with the expected rainfall reductions in the core production regions, the ratio between net orchard water demand and the water supply available for farming is expected to increase.

2.1.2.7 Orchard technologies and management practices

Several technologies and management practices aimed at reducing the stresses on fruit production caused by high solar radiation and temperature have been developed and tested for apple orchards globally and in South Africa. Photothermal stress reduces net CO_2 assimilation (photosynthesis minus respiration of leaves and young fruit) (Gindaba and Wand, 2007b), causes sunburn damage on the fruit surface, leads to undesirable pink blush on green cultivars such as Granny Smith, and can cause reduced green peel colour of green and yellow cultivars through bleaching of the chlorophyll pigment. Technologies such as shade nets, kaolin particle sprays, and evaporative cooling have been found to effectively reduce yield losses through either the reduction in solar radiation and/or the reduction in temperature (Gindaba and Wand, 2005; Smit, 2007). Protective netting also reduces wind damage, and it can be designed to also provide hail protection. The perceived multiple benefits and cost-benefit calculation for protective netting have made this technology the current technology of choice. However, no local studies have yet assessed the possible impacts of the above-mentioned technologies on evapotranspiration and water use of apple orchards, although evaporative cooling clearly increases the water used.

The manipulation of tree structure, training, and pruning, and growth control strategies are also used by growers to reduce light- and temperature-related production problems. Until now the impact of these approaches on tree and orchard water use have not been assessed. However, a recently completed study in the Western Cape showed that apple tree total leaf area is the major determinant of water use per tree and for the orchard (Dzikiti et al., 2018a). Changes in growth and canopy structure under netting require adjusted management practices, which interact with the changed microclimate under the netting in complex ways.

The use of composts and mulching, and the introduction of cover cropping between the tree rows, has benefits for an improved soil structure, soil health and water-holding capacity of apple orchards. However, these practices also introduce complexity into the accurate quantification of soil water content dynamics.

2.1.3 Use of protective netting for apple production in South Africa

As part of this review, we include a summary of the current experiences and opinions held by technical experts in the South African apple industry, with some reference to global expert opinion and developments in the use of shade netting systems for deciduous fruit orchards. Protective netting for the South African fruit industries is supplied by several commercial companies. We do not go into specific product details here, but highlight the fact that several different types of netting are available for different applications and objectives. The main factors to consider are:

- Woven or knitted construction and material used, which determines strength, unit mass in g m^{-2}, and whether or not it frays on the edges
- Colour (white, black, grey, crystal, pearl, green, red, blue, yellow, threads of colour woven into white or black).
- Density (or percentage shading)
- UV-blocking ability (additives)
- Ease of joining sections, and repairing tears

Netting is generally made from high density polyethylene (knitted), polypropylene (woven), or even aluminium. Nets sold in South Africa must have sufficient UV stabilisation to achieve a reasonable life span under the high solar radiation levels experienced. The maximum lifetime for black netting is 15-20 years, whereas white and crystal nets last for around 10 years, with grey net intermediate. Coloured nets have been found to lose colour within a few years under South African conditions (D. Brink, personal communication 2018). Fixed netting systems employ either a flat structure, or a gabled roof structure. Where hail or snow is a risk, nets must be stronger and openable to release the hail/snow accumulated on the net into the row. However, many more benefits of openable nets are emerging in South Africa and these are now finding favour even in regions where hail is not a risk.

Draped netting, which was developed in Australia, has recently been tested in South African apple orchards and the results look very promising (A. Müller, personal communication 2018). In this system the net covers the tree row only and is removed between harvest and fruit set, using a specially developed machine or manually. It is perceived to be more cost-effective, and allows for better crop load control (thinning, bud development after harvest).

Currently, technical advisors and farmers are still testing various systems although large commercial applications have started. There is still very little scientific information to support decision making, and it is likely that the “optimum” system will vary from orchard to orchard (Brink et al., 2015). Cost-benefit is the main concern and this has only been calculated for certain farm trials. Overall, based on current experience, it appears to make greatest economic sense to install shade netting over ‘Granny Smith’ orchards (new and some productive older orchards). However, the negative effects on colour on red and blushed cultivars and the cost of netting are seen to be too great in comparison to the benefits of sunburn reduction. The industry is pursuing the use of more dwarfing rootstocks such as M9 or G222 and better coloured strains of blushed cultivars under netting to overcome some of the challenges. On the other hand, strong vegetative growth in very young trees under netting could be used to advantage to “fill the space” more quickly and advance full-bearing age.

Cultural practices must be adjusted when fruit are produced under netting. These would include choice of rootstock and tree density, pruning and other vigour control methods, pollination and fruit thinning, spray programmes for the control of pests and diseases, nutrition, use of mulching, irrigation system and scheduling, and harvest planning. To update current perceptions and practices, a group of industry technical experts were interviewed during May and June 2018. The results are presented in Table 1.

Table 1 Summary of survey of industry technical experts on the use of protective netting in apple orchards in South Africa.

Parameter	Response (AM) EGVV	Response (WK) KBV	Response (DB/GK) EGVV (but supply to other areas)	Response (PD) SW Cape and Ermelo
Purpose of installing netting	WC: 1. Sunburn reduction; 2. better green colour (Granny Smith) Langkloof: 1. Hail protection, 2. sunburn reduction	WC: 1. Sunburn reduction, 2. growth of young trees, 3. hail protection Langkloof: 1. Hail protection, 2. sunburn reduction	1. Sunburn reduction	
Netting system	WC: draped netting 20%. Install nets after cell division and thinning but before sunburn risk. Timing of installation and removal is critical. Fixed system only where hail is a risk (permanent risk). In new orchards use high density. Row width 3-3.5 m or even 2 m. 3000-4000 trees/ha possible. Optimise light interception (maybe V system) or 2-dimensional row. Langkloof: Hail is a permanent threat.	WC: Flat roof mainly for existing. Old pitched structure not suitable due to impacts on bees and the higher cost. New installations moving to openable structure, with small pitch. European systems (generation 2) with elastics are strong and easy to open and close. Cherries: generation 3 with elastics, closed all year for hail protection. Draped netting is an option, it's cheaper. Suited for older orchards and those on more vigorous rootstocks. Langkloof: Flat roof with gutter to empty the hail. Fixed (permanent) systems with pitch not yet ideal. Tunnel system with open or closed sides will be tested. V systems with netting are still too expensive (R700 000/ha)	Until now – fixed netting, not openable. Are moving to openable netting – new technology available. Especially for Ceres where snow can occur. Also using draped netting now on older but productive Granny Smith orchards to reduce sunburn.	Favours openable netting. Closed (fixed) systems have problems with pollination (bees) and lack of direct sunlight during bud development. Must open the netting straight after harvest and close soon after fruit set but before thinning. Cannot take a chance with hail or sunburn risk. Will be looking at draped netting. Concerned about possible decreased fruit size due to the shading factors, and sub-optimal practices (trade-off between proper thinning and sunburn risk i.t.o. timing of net closure). European (Italian) openable system now being tested in SA. Light penetration is not so good under a flat net structure, best where net is at 30° angle. There must be enough space between top of canopy and the net so that bees can work.

Net colour	WC: Black for Granny Smith to achieve better green colour and sunburn reduction; Higher temperature under white net which can be a risk to red colour development in bicolours. Grey is also an option. Langkloof: White is suited, cooler temperatures in the afternoons.	For draped netting use black woven over green and yellow cultivars. For fixed netting use white or grey knitted over blushed / bicolour cultivars. Grey is suited to high colouring cultivars with high sunburn risk. Use white for cultivars that don't colour as easily but have lower sunburn risk. White-blue net is also an option.	Have tested colour nets but could not demonstrate meaningful differences. Blue nets led to yield decreases. Now using white, blue or white-blue combination. White nets are useful but not in all situations. Grey or black may be better then.	Favours white net, 15% shade factor. Evidence shows that colour nets have no benefits. Black net: most UV resistance White net: least UV resistance Grey: in-between, best option. Italian company making true grey net with 15-year guarantee – now testing this net.
Cultivar	Mainly Granny Smith, one Rosy Glow. Golden Delicious shows less production and quality variability and price differential is lower than Granny Smith.	Draped netting: green and yellow cultivars, especially Granny Smith. Also Kanzi, Rosy Glow, Fuji.	Granny Smith Cripps Pink (Pink Lady), Fuji, Sundowner (colour loss is a challenge). Golden Delicious: maybe but yields may not be high enough for financial benefits. Could benefit from better ground colour.	Granny Smith Ermelo: all cultivars The climate is ideal for red and blushed cultivars, netting does not cause colour problems. For Pink Lady open the nets two weeks before harvest to increase colour. Don't do this for Royal Gala or other sunburn-sensitive cultivars.
Rootstock	Should move towards more dwarfing.	WC: Can use dwarfing (M9) or M7 with Kanzi. MM109/M9 is still useful but not a long-term option. Choices more difficult for Rosy Glow, not so vigorous. Gala and Fuji on M9. Can plant at 3m x 0.8m and achieve full production in year 3-4. Langkloof: Fuji on M9 on high potential soils.		Don't use M793 or MM109 under netting, too vigorous. M7 also marginal. M26 and some of the Geneva selections are showing promise. M9 can also work with nets, enjoys the cooler soil temperatures. Plant at higher density. Rootstock selection is critical.

Orchard age	Use higher densities in new orchards.			Netting over young orchards increases performance by around 30%. Reduced wind and stronger growth of young trees. In Year 4, yield was 25 t/ha (no net) and 40 t/ha (under net).
Irrigation	Using same system and scheduling as in the open. Get more growth though. Rootstock has a large influence. Use Regalis, summer pruning.	Normal monitoring and irrigation. Irrigate separately from open blocks. They have measured ~10% reduced irrigation for Kanzi on M7 under netting.	No data available. One estate estimates a probable reduction in irrigation.	Knows of two farms where water savings of 20-30% are being measured.
Pollination and yield		Pollination (bee activity) is fine under netting. Bud development is fine. Rootstock must be fruitful.		Yield decreases progressively under fixed netting. Thinks that this is a bud development problem. When they open the netting after harvest yield has increased 50%. In Ermelo, all orchards are under fixed netting and yields are progressively decreasing.
Training and pruning	Must manage canopy growth well; excessive growth under nets reduces yield over time. Draped netting pushes young shoots down and helps to control vigour.			Vigour is a problem. Must use Regalis and good pruning practices. For Fuji and Granny Smith use four Regalis sprays per year.
Pests & diseases	Risk of Fusi. Spray program from bloom until end-November. Thereafter preventative monthly sprays. More effective retention and cover of sprays under draped netting. Codling moth – reduced risk, save on sprays.	Mostly no impacts. Moths appear to be reduced in the Warm Bokkeveld under draped netting. Otherwise normal best practice management required. Spray against powdery mildew before draped netting is installed.	Red mites are worse under nets. Do normal pest and diseases management before draped nets are closed, but must do it before the first risk of sunburn. Hail nets must be closed early, during flowering.	Mildew is possible a problem. Fusi is not a problem. Does not see more insect damage.

	Mealybug – maybe higher risk but can be managed. Bollworm, weevil, stink bug, leaf roller – no change, continue normal management. Later flying insects can be reduced.			
Nutrition	Adjustment probably not needed. Not seeing calcium deficiency, can be avoided by putting draped netting up in the early fruit growth period.			
Fruit quality	Significantly better. Massive reduction in sunburn – average cull now is 30%, with draped netting cull is 12%. Better green colour. Less blush on Granny Smith.	Massive reduction in sunburn. Reduced from 30% to 10% cull.	Bicolours: sunburn reduction but also loss of red colour – no economic benefit when that happens. Granny Smith: sunburn reduction and pink blush reduction. Average total sunburn in the open is 20-30%; Class 3 sunburn 30%. Mistakes are made during harvest and pre-sorting, this causes financial losses.	
Return on investment	Instant benefits. Payoff in 1-3 years. Must get the right balance between yield and fruit quality to optimise profitability in the longer term. Significant increase in Class 1 packout (50-60 t/ha Class 1, 70% of harvest).	Payback is fast especially for Granny Smith – one year if yield is high. In Golden Delicious payback is about four years.	Increased profitability in the recent past was achieved with higher yields; further gains will depend on increased Class 1 packouts. Technologies that can achieve this will pay back. Netting is cost-effective.	Payback time for Granny Smith is around 2 years.

			Payback in Granny Smith is under 2 years. In Golden Delicious it will be longer.	
Netting costs	For 8 m draped netting width: R100 000/ha. Installers can do 7 ha/day in Australia, in SA they do 5 ha/day. Having labour to put net up at the right time and speed is a limitation.	Fixed system: R120 000 to R150 000/ha. Draped netting system: for 7-8 m net width – between R84 000 and R130 000/ha depending on tree density.	Draped netting is more cost effective than fixed netting.	New systems are costing around R190 000/ha.
Additional costs	Small increase in labour cost.	Challenges with availability of machinery and labour on large farms. Draped nets need more labour (or platforms) and storage in winter.		New European openable system is labour-efficient. Two labourers can open/close 2 ha in one day.
Current installations	Close to 10 ha in EGVV, all Granny Smith except one Rosy Glow orchard. Significant installations planned for Granny Smith over next few years.	WC: Netting good option in high potential soils. New plantings – should try to use nets, but management of netted orchards is more intensive and this is a consideration. Langkloof: All new plantings under nets.		
Incentives	Multiple benefits. Water use benefits would encourage uptake. Plant solid rows of Granny Smith with draped nets – profitable.		Reduced water use would be seen as an additional benefit.	

2.2 WATER PRODUCTIVITY OF APPLE ORCHARDS

The analysis of WP can usefully guide apple growers towards more sustainable irrigation and orchard management practices and long-term decision-making for continued profitability using less water.

"Water productivity is the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water used to produce those benefits. In its broadest sense, it reflects the objectives of producing more food, income, livelihood and ecological benefits at less social and environmental cost per unit of water consumed" (Molden et al., 2010). In this study, we are interested in the physical water productivity (WP_p), defined as kg of fruit produced m^{-3} of water used based on either transpiration or evapotranspiration. We also assess the economic water productivity (WP_e) of the orchards, defined as the gross orchard income (in South African Rand) derived m^{-3} of water used.

Opportunities exist in the South African apple production environment to increase WP. This could entail producing more fruit per unit volume of water used, using existing water allocations and rainfall more efficiently for productive outcomes, or increasing the value of the harvest without increasing the water use. If the use of protective netting reduces tree and/or orchard water use without negatively affecting marketable yield (and more likely increasing this), it is very likely that this technology can provide the benefit of increased WP.

2.3 EFFECTS OF PROTECTIVE NETTING ON ORCHARD MICROCLIMATE

The use of protective netting over orchards alters the microclimate under the netting compared to that of similar orchards in the open (Jifon and Syvertsen, 2003; Tanny et al., 2009; Solomakhin and Blanke, 2010a; Bastías and Corelli-Grappadelli, 2012; Kalcsits et al., 2017; Mupambi et al., 2018). The most significant changes occur in solar radiation intensity, canopy radiation interception, and spectral quality of the radiation. Changes in the diurnal fluctuations of air, canopy and soil temperatures, changes in air relative humidity and vapour pressure deficit, as well as changes in wind speed and boundary layer characteristics may also occur. These changes modify both the energy and water balance underneath the netting which in turn affect key physiological processes including transpiration rates. We briefly explore these microclimatic changes, referring to existing reviews, before discussing the impacts of the changes on energy and water balance and orchard water use, the primary focus of this knowledge review.

2.3.1 Solar radiation

Mupambi et al. (2018) point out that changes in the spectral quality and solar radiation (shading factor) under netting are determined by the type of net, the mesh size and the colour (Shahak et al., 2004a; Castellano et al., 2008; Blanke, 2009; Shahak, 2014). For apple orchards, shading factors between 10 and 30% are most appropriate and widely used. Black net generally has a higher shading factor than the equivalent white net, with grey net having an intermediate shading factor. The shading factor usually increases over time owing to dust accumulation and pigment degradation. The design of the net installation and especially the angle of the net to the sun's rays also influences the alterations in solar radiation (Castellano et al., 2006), with an angled structure allowing more direct rays to penetrate through the mesh. The transmission of diffuse (scattered) radiation increases under netting, with the relative increase being much greater on a clear compared to a cloudy day (McCaskill et al., 2016). This increases light penetration into internal areas of the canopy that receive little direct radiation under clear sunny conditions (Lakso and Musselman, 1976). Black and grey nets decrease the solar radiation throughout the canopy (Bosco et al., 2018) but relatively less so in the lower canopy compared to trees in the open (Treder et al., 2016), whereas white nets decrease solar radiation in the lower zone (Treder et al., 2016). Such trends are likely to be influenced by planting density and training system (Bosco et al., 2018).

An important feature of the changes in spectral quality is the enrichment in near infra-red (NIR) wavelengths (760-1500 nm) under netting compared to the open. The reduction in photosynthetically active radiation (PAR, 400-700 nm) is the same across the PAR wavelengths in non-coloured nets (black, white, grey), whereas transmission of ultraviolet-B (UV-B) radiation (280-315 nm) is reduced (Basile et al., 2012; McCaskill et al., 2016) but more so under white than black nets (Solomakhin and Blanke, 2010a). The ratio of red to far red (R:FR) radiation is not usually altered (Mupambi et al., 2018) with some exceptions (e.g. Bastías and Corelli-Grappadelli, 2012). Under photo-selective coloured nets (e.g. red, blue, green) significant alterations in light quality are measured (Basile et al., 2012), since these are intended to induce specific physiological and growth responses in the crop (Shahak et al., 2004a; Solomakhin and Blanke, 2008, 2010a; Bastías et al., 2012; Kalcsits et al., 2017). In this review we will focus primarily on the physiological effects of non-coloured nets rather than the wide range of coloured nets, since the former are now almost exclusively installed in South African apple orchards. Farm trials with coloured nets did not indicate meaningful benefits in comparison with cheaper non-coloured nets, although some growers are installing nets with a blue thread in the weave for its vigour-reducing properties (D. Brink and G. Krige, personal communication 2018).

2.3.2 Temperature, relative humidity and vapour pressure deficit

Temperature of the air, canopy and soil under netting compared to the open can vary widely, and can be both lower and higher, or the same (Middleton and McWaters, 2002; Jifon and Syvertsen, 2003; Gindaba and Wand, 2007a; Kalcsits et al., 2017), as discussed by Mupambi et al. (2018). This is because temperature is the outcome of a complex interacting set of factors including solar radiation and the shading factor of the net, position of the sensor in the canopy or soil, changes in air circulation (usually reduced, the “greenhouse effect”), and local climate. Even within the same trial, results can vary from year to year (Bosco et al., 2018). Nevertheless, air and leaf temperatures are frequently reduced (Middleton and McWaters, 2002; Gindaba and Wand, 2005, 2007a; Iglesias and Alegre, 2006; Smit et al., 2009; Solomakhin and Blanke, 2010a). The transpirational cooling of an apple leaf under netting is higher on a sunny warm day than on an overcast cooler day, and is higher under dark netting (with a higher shading factor) than under white netting (Tanny et al., 2009; Solomakhin and Blanke, 2010a). Differences in air temperature between covered and open orchards are also less pronounced on windy days (Solomakhin and Blanke, 2010a).

Increases in air temperature under netting can occur where air circulation is significantly reduced (Iglesias and Alegre, 2006), or when the sensor is placed very close to and high up underneath the net where the warm air rises and may gather (Ebert and Casierra, 2000). Minimum nighttime temperatures have been found to increase under netting due to a decrease in radiative cooling (Bosco et al., 2018) whereas maximum temperatures (Iglesias and Alegre, 2006) can be reduced due to the reduction in solar radiation. This can result in a reduction of around 2°C in the daily temperature range under netting (Tanny et al., 2009). Tanny et al. (2009) observed that the most pronounced temperature differences occurred from 10:30 to 15:30 and from 20:30 to 06:00.

Only a few studies have measured soil temperatures under protective netting. Solomakhin and Blanke (2010a) reported that soils under white or near-white nets (5 cm depth) were up to 0.9°C warmer in and between the rows compared to open orchards, whereas soils under darker nets were up to 1.0°C cooler in the tree row and up to 0.5°C cooler in the alleyway. This difference was ascribed to the greater shading factor of dark nets and lower direct radiation penetration. Different colour nets in the Kalcsits et al. (2017) study reduced soil temperature at 20 and 40 cm depths compared to the open, but to different degrees. Changes in soil temperature are important with respect to orchard water use since they can affect the evaporative component of evapotranspiration and may also influence root activity.

Fruit surface temperatures generally decrease to a greater degree under nets than leaf surface temperatures (since fruit do not employ transpirational cooling), and more so under dark than under white nets (Solomakhin and Blanke, 2010a). Kalcsits et al. (2017) found significant reductions of 2.6 to 4.3°C in maximum fruit surface temperature on a sunny day under netting in Washington State, USA, compared to the control. Similarly, reductions of 4.0 to 5.3°C were reported by Smit et al. (2009) on a sunny warm day in South Africa, but only 0.7 to 2.9°C on milder days. The greatest difference in fruit surface temperature are found during the warmest part of the day (Gindaba and Wand, 2005; McCaskill et al., 2016). One can therefore conclude that the installation of protective netting in climates with high solar radiation and temperatures in summer (such as Mediterranean-type climates) are more likely to show larger reductions in air, leaf and fruit surface temperatures compared to milder temperate climates with often overcast conditions. The potential fruit surface heating effect caused by the significant reduction in wind speed under nets has been found to be more than offset by the reduction in solar radiation load and the increased component of diffuse radiation (McCaskill et al., 2016). Fruit surface temperature at night was observed to be similar under netting and in the open (McCaskill et al., 2016).

The influence of protective netting on air RH is variable and depends on many factors including the RH in the open, the temperature, the wind speed inside and above the canopy, the irrigation system and scheduling together with rainfall, and the orchard density (Mupambi et al., 2018). Increases in RH by as much as 10-15% have been reported in Australia where ambient RH in summer is low (Middleton and McWaters, 2002). In contrast, no differences in RH were found in a netted citrus orchard in the humid climate of Florida, USA, (Jifon and Syvertsen, 2003) or in the drier apple production region of Washington State, USA (Kalcsits et al., 2017). In the humid temperate climate of Germany, RH was increased under white nets by 1-3%, linked to increased air temperatures (Hunsche et al., 2010) and by 2-5% in another study (Solomakhin and Blanke, 2010a). Similar increases were reported by Iglesias and Alegre (2006) in Spain. Changes in RH in an orchard in southern Brazil depended on the canopy stratum and year, but the dominant trend was a moderate increase (3-9%) in RH under nets (Bosco et al., 2018). McCaskill et al. (2016) reported increases in RH only at night.

Both wind speed and relative humidity in an orchard determine the leaf wetness duration (LWD), a parameter sometimes used for disease monitoring. LWD was found to be higher under nets in the Brazilian study (de Paula et al., 2012). This was true for all strata of the canopy, but the differences were significant in the upper and middle parts of the canopy which had lower LWD compared to the lower parts. In South Africa, Gindaba and Wand (2007a) found no differences in leaf-to-air vapour pressure deficit (VPD_{leaf}) when gas exchange was measured on apple leaves under and outside protective netting. However, in a different study, significant reductions in VPD_{leaf} were measured on four apple cultivars under nets in two seasons (Smit, 2007; Smit et al., 2009). Shaded potted grapefruit and orange trees also had a significantly lower VPD_{leaf} and values were closely related to changes in leaf temperature (Jifon and Syvertsen, 2003). VPD_{leaf} is influenced by the air and leaf surface temperatures, the RH of the air (the RH of the sub-stomatal cavity is assumed to always be 100%), and the thickness of the leaf boundary layer which is strongly determined by wind speed over the leaf surface. Given that temperatures are generally reduced under nets, RH is often increased, and wind speed is significantly reduced, it follows that under most netted conditions the VPD_{leaf} can be expected to decrease. At a canopy level, netting impedes vertical air flows, raises RH and consequently increases and stabilises the canopy boundary layer (Tanny et al., 2009). These changes have direct implications for leaf and canopy transpirational water loss.

2.3.3 Wind speed

Fruit surface temperatures are determined by air temperature, solar radiation and wind speed, together with fruit dimensions and shape which influence the boundary layer. Wind is also an important factor in determining the boundary layer and vapour pressure deficit between the leaf and the surrounding air, thus influencing transpirational water loss. It is thus surprising that the influence of protective netting on wind speed and air circulation in orchards has only been studied relatively recently. Australian researchers (Middleton and McWaters, 2002) measured wind speed reductions at the canopy level of up to 50% compared to the control, and in Washington State, USA, netting reduced the wind speed by 40% at all times for the duration of the trial (Kalcsits et al., 2017). In southern Brazil the reduction in wind speed at the top of the canopy was about 30% (Bosco et al., 2018). In these studies flat netting was used; no data are available for draped netting. The structure of the netting installation (e.g. sides open or closed), and net properties such as structure and density will influence the degree of reduction in wind. Tanny and Cohen (2003) and Tanny et al. (2009) showed, in detailed studies of the effects of nets on the properties of wind and the canopy boundary layer of covered citrus and apple rows, that the nets act as a barrier to vertical air movement and this enhances atmospheric stability. They suggested that this must potentially reduce the atmospheric water demand of trees under nets compared to the open.

2.3.4 Actual evapotranspiration

Very little quantitative evidence exists for the impact of protective netting on actual evapotranspiration in fruit orchards. Using a verified model, McCaskill et al. (2016) found that evapotranspiration was 13% lower under netting than without (159 vs 183 mm/month), due to reductions in wind and solar radiation and increases in RH. Penman-Monteith-based calculations of evapotranspiration of apples (Prokopljević et al., 2012) and peaches (Girona et al., 2012) under netting also indicated significant reductions compared to the open.

2.3.5 Soil water content

Similarly, very few studies have reported on changes in soil water content under netting. In Smit's study (Smit, 2007), the farm management provided information on soil water content under and outside netting, and no differences were found in the 'Royal Gala' and 'Cripps Pink' orchards. However, soil water content was higher under netting in the 'Fuji' orchard compared to the control under the same irrigation regime. Middleton and McWaters (2002) measured soil water content at four depths in a three-year-old ‘Royal Gala’ orchard under white nets in a dry region of Australia. Soil water content tended to decline more slowly under the net relative to the open. Kalcsits et al. (2017) also measured increases in volumetric soil water content at 20 and 40 cm depths under coloured nets throughout the study period compared to the uncovered control. The increases ranged between 13.2% (pearl), 16.3% (red) and 18.6% (blue) 20 cm depth, and between 17.0% (blue), 20.0% (red) and 24.4% (pearl) at 40 cm depth. The authors point out that soil water content measurements using capacitance sensors can be affected by soil temperature and that this can affect the data. The temperature differences in this study were not large enough to explain the observed differences in soil water content.

2.4 EFFECTS OF PROTECTIVE NETTING ON ECOPHYSIOLOGY, WATER USE AND REPRODUCTION

2.4.1 Leaf gas exchange and WUE

Shade leaves of most plant species typically have a lower photosynthetic capacity, reduced dark respiration rate and lower leaf nitrogen concentration (Lichtenthaler et al., 1981; Lambers et al., 1998; Larcher, 2003; Oguchi et al., 2003). In some studies on fruit trees under protective netting this has been confirmed. Nevertheless, there have been reports of increased photosynthetic capacity in fruit trees under moderate-density shade netting and under certain conditions (Ebert and Casierra, 2000; Jifon and Syvertsen, 2003; Nicolás et al., 2005; Smit, 2007), or no responses in photosynthesis rate (Massachi et al., 2000). We will discuss each of these outcomes and their underlying explanations.

Apple leaf net photosynthesis rate (net CO_2 assimilation rate) increases linearly with increasing PAR at solar radiation levels below the light saturation point, whereafter the rate increase slows to zero and the maximum light-saturated net photosynthesis rate is reached. The light saturation point is approximately 800 µmol m^{-2} s^{-1} PAR in temperate production regions such as Germany (Solomakhin and Blanke, 2008), but is closer to 1000 µmol m^{-2} s^{-1} or even 1200 µmol m^{-2} s^{-1} in lower latitude production regions with high maximum solar radiation in summer, such as South Africa. Reductions in net photosynthesis rate are commonly found where protective netting reduces PAR to below the light saturation point. This is experienced under cloudy conditions where lower PAR on the outside is already limiting photosynthesis, or early in the morning and late in the afternoon when irradiance is low, or under darker netting with a high shading factor. If above-saturating PAR levels are used when measuring leaves inside and outside the netting, no differences in photosynthesis rate are found, confirming that they are light-limited (Romo-Chacon et al., 2007; Solomakhin and Blanke, 2008).

Widmer (1997) and Stampar et al. (2001) generally measured no differences, but Widmer (1997) in Switzerland reported reductions in net photosynthesis rates under netting during periods of low irradiance (cloudy or foggy). Ebert and Casierra (2000), in Germany, found lower net photosynthesis rates under netting in the morning but higher for the rest of the day compared to trees in the open. They attributed this increase to lower dark respiration rates later in the day linked to reduced leaf temperatures relative to the control. A similar daily trend was reported for citrus in Spain by Nicolas et al. (2008). In South African production regions, cloudy conditions in summer are relatively rare, but potential reductions in net photosynthesis rate would be possible during the morning (Gindaba and Wand, 2007a) before the onset of stressful conditions with reductions in gas exchange. The same could apply to shaded or semi-shaded leaves inside the canopy but this has not been studied.

In lower latitude fruit production regions such as South Africa, Italy, Israel, Florida and Australia, clear days in the growing season are characterised by high irradiance and high leaf temperatures, thus high energy absorbed by the leaves. For example, maximum PAR under clear sky conditions in midsummer in the Western Cape province of South Africa is about 1800-2100 μmol m^{-2} s^{-1}. A 20-30% reduction under shade netting would not reduce available light to levels below that required for photosynthetic saturation in exposed apple leaves, about 1000-1200 μmol m^{-2} s^{-1} PPFD.

In fact, protective netting can reduce stress exerted on the photosystem and increase net photosynthesis rate in two ways. First, leaves of C_3 plants, such as apple, have a high rate of photorespiration when exposed to high irradiance and temperature, which reduces the efficiency of photosynthesis (Larcher, 2003). This can be measured as a high CO_2 compensation point of photosynthesis. Shade netting can reduce leaf temperature and photorespiration rate under high ambient irradiance conditions during the midday, as shown by a lower CO_2 compensation point (Gindaba and Wand, 2007b).

Second, PAR that exceeds the PAR saturation level is absorbed by chloroplasts where it can damage the photosystems and lead to photoinhibition (Losciale, 2008). Photoinhibition commonly reduces leaf carbon gain on clear and hot days, but this can be reduced under netting as indicated by significantly lower reductions in maximum photosystem II photochemical efficiency (F_v/F_m) compared to the control (Jifon and Syvertsen, 2003; Olivares-Soto and Bastías, 2018). In fact, removal of the excess radiation and thus absorbed energy can explain why net photosynthesis rate is not reduced, and can even increase, under protective netting in low latitude regions with mostly clear sky conditions in the growing season (Losciale, 2008; Smit et al., 2009).

We now turn our attention to the factors which affect net photosynthesis rate and transpiration rate through impacts on stomatal conductance and the regulation thereof. Stomatal opening is directly responsive to light in the blue and red spectral range (Shimazaki et al., 2007). Where protective netting alters the spectral quality of light, changes in stomatal opening could be expected (Jifon and Syvertsen, 2003). Black and white netting is spectrally neutral and only coloured photoselective netting could elicit such a response. More importantly, protective netting alters the temperature and humidity environment of the leaves (Middleton and McWaters, 2002; Jifon and Syvertsen, 2003; Shahak et al., 2004b) with associated effects on stomatal conductance and transpiration. Leaf transpiration rate is determined both by the vapour pressure deficit between the leaf and the surrounding air (VPD_{leaf}), and the stomatal control of fluxes of water vapour and carbon dioxide (CO_2). Shade netting can reduce VPD_{leaf} (Jifon and Syvertsen, 2003), potentially leading to higher stomatal conductances, net photosynthesis rates and transpiration rates. Studies which have reported increased stomatal conductances under nets include Jifon and Syvertsen (2003); Nicolás et al. (2005); Smit (2007); and de Freitas et al. (2013).

Smit (2007) found that the level of regulation of stomatal conductance was pronounced during hotter parts of the pre-harvest season, from January to March, and particularly from mid-morning to mid-afternoon. During these periods, VPD of ambient air in the open was about 2-4 kPa, but lower under netting, and stomatal conductances and net photosynthesis rates were in most cases higher under the netting. On milder days and late in the season, conductance and photosynthesis values did not differ between trees under netting and in the open. Nicolás et al. (2005) reported that shaded peach trees opened their stomata later in the morning than exposed trees, but stomatal conductance was always higher than in exposed trees during the central hours of the day (between 10:00 and 16:00).

The influence of protective netting on leaf level transpiration rate is usually closely coupled to the stomatal response, with greater/lower stomatal conductance leading to greater/lower transpiration rate. Thus the response will be as variable as that of stomatal conductance, as discussed above. Nevertheless, atmospheric demand for water also plays a significant role in driving the transpiration rate at a given conductance, and this is influenced primarily by VPD_{leaf} and leaf temperature. Gindaba and Wand (2007a) found that 35% shade under netting reduced solar radiation and leaf surface temperature sufficiently to result in reduced transpiration rate compared to the open (control) treatment, although no significant differences were found for stomatal conductance or VPD_{leaf}. Massachi et al. (2000) also recorded reduced transpiration under 30% shaded conditions in cherry sapling. In temperate climates such as Germany, the reduction of solar radiation under the light saturation point, such as on a cloudy day, is likely to result in decreased photosynthesis rate, stomatal conductance and transpiration rate (Solomakhin and Blanke, 2008).

Recent shade net installations for apple orchards strive to optimise the shading factor so that negative effects on gas exchange are prevented. In another South African study, Smit et al. (2009) used four apple cultivars and a lower shading factor than Gindaba and Wand (2007a). In the first year, reduced leaf temperature and VPD_{leaf} led to increased stomatal conductance in all cultivars. 'Royal Gala' showed the largest decreases in VPD_{leaf} and T_{leaf} and the largest increases in stomatal conductance, photosynthesis rate and transpiration rate in mid-March when the leaves of control trees showed signs of photosynthetic downregulation following the completion of the harvest. The other three cultivars showed no change in transpiration rate, linked to more moderate increases in stomatal conductance and moderate decreases in VPD_{leaf}. This suggests that under these conditions higher stomatal conductance was countered by the lower VPD_{leaf} to result in similar transpiration levels.

A similar effect of netting on leaf level transpiration rate was reported by Jifon and Syvertsen (2003) in Florida. Although stomatal conductances were higher in shaded than control leaves of citrus species, VPD_{leaf} was lower for shaded leaves compared to control leaves, and leaf transpiration rates did not differ between the treatments. The literature supports the concept that the leaves of fruit trees may regulate their stomata to maintain a stable transpiration rate over a wide range of VPD_{leaf}. The level of VPD_{leaf} at which stomatal closure prevents further increases in transpiration as VPD_{leaf} continues to rise, thus stabilising leaf and stem water potential at a "safe" level to prevent xylem embolism, differs between fruit tree species (Jones et al., 1985). In citrus and other isohydric[1] species, this level is relatively low (ca. 1.5-2 kPa) whereas in apple (an anisohydric[2] species) it has been shown to be around 3 kPa in warm climates.

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[1] Plants with isohydric behaviour maintain a constant midday leaf water potential when water is abundant, as well as under drought conditions, and across a wide range of atmospheric evaporative demand, by reducing stomatal conductance as necessary to limit transpiration (Tardieu and Simonneau, 1998).

[2] In plants with anisohydric behaviour, daytime leaf water potential markedly decreases with an increase in atmospheric evaporative demand and stomatal conductance is kept high to maximize photosynthetic rates for longer periods, even under conditions of moderate water stress. However, beyond a certain threshold in evaporative demand, stomatal regulation is employed to prevent further dangerous reductions in water potential evaporative demand.

In Smit's second study year, T_{leaf} and VPD_{leaf} were decreased on hot mid-summer days in all cultivars except 'Fuji' (which was measured on a milder day), and photosynthesis rates and stomatal conductance were increased when measured at the height of summer in mid-January (Smit et al., 2009). All cultivars except 'Fuji' had a higher leaf transpiration rate under netting compared to the controls.

In the plant ecophysiological literature, two measures of leaf photosynthetic WUE are used. Instantaneous water use efficiency (WUE_{inst}) is calculated as the ratio of photosynthesis rate to transpiration rate (A/E) (μmol CO_2 $mmol^{-1}$ H_2O) – this represents the immediate trade-off between carbon gain and water loss (Farquhar et al., 1989; Cheng and Luo, 1997). Intrinsic water use efficiency (WUE_{intr}) is the ratio of photosynthetic rate to stomatal conductance (A/g_s) (μmol CO_2 mol^{-1} H_2O) – this ratio is less dependent upon instantaneous environmental conditions such as air temperature and relative humidity, compared to WUE_{inst} (Comstock and Ehleringer, 1992). It is negatively correlated with the carbon isotope discrimination ($\Delta^{13}C$) measured over the leaf lifespan and is believed to be under tight genetic control in many tree species (Massonet et al., 2007). Apple stomata in the field are normally highly coupled to photosynthesis, avoiding excessive opening, and maintaining very good WUE (Lakso, 2014).

Very few published studies have reported on the effect of protective netting on WUE_{inst} or WUE_{intr}. When low irradiance under netting reduced apple leaf temperature and transpiration rate, WUE_{inst} was increased relative to the control (Gindaba and Wand, 2007a). In citrus species, WUE_{inst} was higher in leaves under shading than those outside during the midday period, and this was ascribed to a stimulation of photosynthesis, with no effect on transpiration (Jifon and Syvertsen, 2003). On the other hand, no changes in WUE_{intr} were found in grapevines grown under or outside netting (Martínez-Lüscher et al., 2017).

In some published studies, significantly enhanced WUE_{inst} can be inferred from results of photosynthesis and transpiration rates (Massachi et al., 2000). Changes in WUE under shade netting still need to be confirmed in South African apple orchards.

2.4.2 Leaf and stem water potential

High rates of transpiration lead to the development of low leaf and stem water potential if the supply of water from the roots does not match the losses at leaf level. In studies of apple and apricot trees growing under netting, midday leaf water potential (Ψ_{leaf}) was increased under the nets compared to the open (Shahak et al., 2004a; Nicolás et al., 2005; Smit, 2007; de Freitas et al., 2013). Smit (2007) measured significant differences on warm days when Ψ_{leaf} values in the unnetted treatment were less than -2 MPa due to soil drying since the last irrigation event. Apple trees, being anisohydric, can allow for the development of considerably low water potential at midday, and these results suggest that netting ameliorates such low values. On days when midday leaf water potential was greater than -1.8 MPa no significant differences were measured between net and control treatments.

Typical isohydric fruit species, however, have often shown no differences in leaf water potential between netted and unnetted treatments. In these cases, Ψ_{leaf} was maintained at no less than -1.3 MPa (Martínez-Lüscher et al., 2017 for grapevine) or -1.1 MPa (Jifon and Syvertsen, 2003 – citrus species) in the open and this did not differ under netting. The exception is the study by Alarcón et al. (2006) who measured the diurnal course of leaf water potential in young lemon trees growing in

Spain, and found reductions under netting throughout the day. Shaded trees also had lower daily maximum daily shrinkage (MDS) of the trunk diameter. Shaded and unshaded peach trees showed similar trends (Nicolás et al., 2005). MDS is closely related to stem water potential (Simonneau et al., 1993) and often increases in water-stressed plants.

2.4.3 Vegetative growth and whole tree transpiration

The critical role of light (both quantity and quality) in fruit tree growth and structural development is well studied (Palmer, 1977, 1989; Jackson, 1980; Tustin et al., 1992; Baraldi et al., 1994; Lakso, 1994; Bepete and Lakso, 1998; Corelli-Grappadelli, 2003; Green et al., 2003; Corelli-Grappadelli and Lakso, 2007; Bastías and Corelli-Grappadelli, 2012). It now forms the basis for modern tree management aiming to optimise light interception, yield and fruit quality. The move towards the installation of protective netting structures in South African apple orchards is expected to require a fundamental re-assessment of current practices such as rootstock choice, tree arrangement and training systems, pruning strategies, renewal of fruitful bearing positions, crop load decisions, and the achievement of balance between root and shoot growth. The physiological mechanisms which are at play under conditions of reduced solar radiation include carbohydrate production (Wünsche et al., 1996) and partitioning (Tustin et al., 1992; Corelli-Grappadelli et al., 1994), dynamics of plant growth regulators (De Wit et al., 2016) and particularly apical dominance, changes in the action of photoreceptors involved in photomorphogenic responses (Baraldi et al., 1994; Gilbert et al., 2001), and possibly water relations. An increase in vegetative growth and vigour is a common outcome under netting (Raveh et al., 2003; Bastias, 2011).

Mupambi et al. (2018), in their recent review of the literature, found that shoot growth responses to protective netting can be variable, differing between studies depending on colour and shade density of the netting, and the cultivar. In one study, numbers of year-old-shoots, lengths of one-year-old shoots, and total length of one-year-old shoots increased in ‘Pinova’ apple trees under all types of netting tested, but only the more dense green-black netting had this stimulatory effect in ‘Fuji’ apple trees on number of shoots and total length of shoots (Solomakhin and Blanke, 2008). In the latter, trunk cross-sectional area was significantly reduced under green-black netting. These effects were explained as a “shade avoidance” response involving the photoreceptor, phytochrome, which exerts control over shoot tip growth (Brutnell, 2006). This growth allows young leaves to reach a position in the outer canopy with higher irradiance. There appears to be a positive relationship between increased shading and the shoot growth response in ‘Fuji’ (Solomakhin and Blanke, 2008). However, stimulation of shoot growth was not accompanied by reduced annual trunk growth (cross-section area) in ‘Pinova’. The cultivar differences were ascribed to the greater alternate bearing characteristics of ‘Fuji’ compared to ‘Pinova’ (Solomakhin and Blanke, 2010a). Cultivar-specific responses were also reported by Treder et al. (2016), with black and gray nets stimulating tree growth of ‘Šampion’ apple trees but not ‘Rubinstar’.

An increase in trunk cross-sectional area of fruit trees under netting compared to the open appears to be a common response especially under darker nets with a higher shading factor where an increase in photosynthetic rates was measured (Iglesias and Alegre, 2006). Coloured, or photoselective nets, show differential impacts on fruit tree vegetative vigour and branching, amongst others, as discussed by Bastias et al. (2012), Giaccone et al. (2012) and Shahak et al. (2014). This will not be discussed in this review in detail. The main findings of these studies are that different colours give widely ranging effects, with red netting consistently increasing vigour and blue netting reducing vigour, for example. These responses result from different red to far red ratios (R:FR) in the light penetrating through the coloured netting. It has been suggested that these effects could be harnessed for efficient vegetative and reproductive growth regulation of perennial fruit crops (Bastias et al., 2012; Basile et al., 2014).

Although the impact of netting on individual leaf area has been studied, we found no publications reporting the changes in total canopy leaf area of fruit trees under netting compared to the open. This was surprising given the significant effects on shoot numbers and shoot lengths discussed above. Total leaf areas is a critical parameter for the assessment of whole tree transpiration and orchard evapotranspiration.

Whole-tree transpiration of apple trees is driven primarily by VPD of the air and solar radiation (as environmental factors) and by canopy leaf area (as a tree factor) (Lakso, 2003; Dzikiti et al., 2018 a,b). It follows that, under protective netting, changes in these factors could be expected to drive changes in tree transpiration. However, protective netting could also be expected to change the canopy conductance through reduced wind speed and altered coupling of the canopy with the atmosphere. Transpiration is also constrained by the hydraulic characteristics of the xylem tissues in the root-stem-leaf continuum, which are to a large degree influenced by the scion species and the rootstock.

A few studies have directly compared the sap flow rates of fruit trees under shade nets and in the open. Sap flow techniques have been used in a study on young pot-grown lemon trees under 40% Aluminet (a highly reflective aluminised polypropylene shade material) (Alarcón et al., 2006; Nicolás et al., 2008). Maximum and minimum daily sap flow was reduced from 1.84 L to 1.24 L (day 242) and from 1.21 L to 0.76 L (day 245) under the netting compared to the open (Alarcón et al., 2006). Sap flow reductions in the shade occurred on every day. For similar leaf conductance values, it was calculated that transpiration should be more than 45% higher for trees in the open compared to shaded trees. However, lower stomatal conductances in exposed trees partially compensated for the effects of radiation changes on water use.

Subsequently, Nicolás et al. (2008) calculated that the decoupling coefficient was higher in the shaded lemon trees compared to exposed trees. In other words, stomatal regulation in the exposed trees controlled whole-tree transpiration effectively, whereas the transpiration of shaded trees was primarily determined by radiation reaching the trees, with much lower stomatal control. This effect was more evident in the afternoon. Canopy conductance values did not differ between the treatments.

In a similar study on young apricot trees (Nicolás et al., 2005), daily sap flow was reduced in shaded trees by 10-20% compared to exposed trees, despite the higher stomatal conductance in shaded trees. This result was complicated by a hysteresis in the diurnal patterns of stomatal opening, leaf transpiration and sap flow, with sap flow being lower in shaded trees in the morning until around midday, but higher compared to exposed trees after midday until sunset.

Nicolás et al. (2005) is the only study to report on changes in plant hydraulic resistance in fruit trees under netting and in the open. Irrigated shaded potted peach trees had lower hydraulic resistance than irrigated exposed trees, suggesting that soil water deficits occurred in the latter, and linking with the lower stomatal conductances in these trees.

In another study on citrus in Israel, Cohen et al. (1997) investigated the water relations of citrus trees under different levels of shading. The nets reduced the net radiation above the canopies by 53% for the dense and 27% for the sparse nets. The leaf stomatal conductance was higher under dense than sparse netting. Despite the high stomatal conductance, the daily midday sap flow was reduced by between 6 and 11% under the dense nets while that under the sparse nets was only 6-7% lower than the trees in the open. The lower sap flow rates under nets were a consequence of the reduced radiation levels which is a key driver of evaporation.

In South Africa, detailed quantitative studies on the impacts of shade nets on orchard water use have been done on citrus. A farmer growing Satsuma mandarin trees under nets and in the open in the Citrusdal area reported that 20% white nets reduced his orchard water use by around 20%. The yield increased by between 15 and 20% per year mainly due to the reduction in wind damage and sunburn. The study also showed that trees under dark nets (red and yellow) used slightly more water than those under white and transparent shade nets (Stander and Cronje, 2016). It is not possible to assess the scientific significance of the reported trends or underlying mechanisms in this popular article.

The above results on whole tree transpiration require verification in field-grown young and older fruit orchards, and for different fruit species. As far as we are aware, only one study has quantified sap flow in apple orchards under shade nets. This study was done in Australia on 'Granny Smith' apple trees by Goodwin and Green (2012) using the compensation heat pulse velocity sap flow method. However, the study did not compare the water use rates under shade nets and outside the nets which is a critical addition in the current WRC/Hortgro project.

While a small number of studies have measured reduced transpiration of fruit orchards under netting, the effect of netting could be more complex. We need to consider the change in solar radiation, wind speed and VPD of the air (combined, they are likely to lead to reduced transpiration), the stomatal regulation of gas exchange in response to the shading factor and the diurnal course of leaf and stem water potential (both increases and decreases in transpiration are possible), and the change in total canopy leaf area and light interception. The effect of the latter has not been studied. It is possible that a stimulation of vegetative growth, including more and longer shoots with additional leaf area, could increase whole tree transpiration, in the absence of effective canopy management strategies. With additional pruning, or the use of a more dwarfing rootstock to control vigour, any transpiration increases could be negated. Another factor which has not been considered in research is the impact of diffuse radiation reaching inner and lower canopy leaves and stimulating stomatal conductance, photosynthesis and leaf transpiration. Heavy shade reduces photosynthesis more than transpiration (low WUE_{inst}) and exposing more leaf area to diffuse sunlight could increase the WUE_{inst} of the whole canopy (Lakso, 2014). A careful analysis of tree water relations and water use under netting must therefore include measures of canopy leaf area and the proportion of illuminated leaves.

2.4.4 Evapotranspiration and orchard water use

Orchard evapotranspiration is comprised of two components: transpiration of the canopy and evaporation from the orchard floor. We have shown that the effects of protective netting on transpiration is complex and responds to a wide range of factors. Detailed measurements of energy balance components and sap flow were conducted by Möller et al. (2004) within an insect-proof screenhouse cultivated with sweet pepper. Modelling (based on a modified Penman-Monteith equation incorporating an additional boundary layer resistance) and validation using sap flow data indicated that transpiration rates of actively growing peppers inside the screenhouse were 1.8-2.1 mm day^{-1} compared to peppers grown outside (4.5-5.3 mm day^{-1}). Model sensitivity analysis showed that reduced solar radiation and wind speed and altered vapour pressure deficit were the main factors influencing transpiration. Calculations of the decoupling coefficient Ω (see Jarvis, 1985; Jarvis and McNaughton, 1986) suggest that the screenhouse evaporative climate is predominantly ‘‘decoupled’’.

Jarvis (1985) explained the concept of “coupling” as follows: “The concept of coupling between leaves and atmosphere is described in terms of the water vapour saturation deficit. Leaves are considered to be well-coupled to the atmosphere if the atmospheric saturation deficit is imposed on the leaf surface without local adjustment: they are poorly-coupled to the atmosphere if the surface saturation deficit finds its own value by local equilibration. Transpiration is considered to be made up of an imposed component, driven by the atmospheric saturation deficit and regulated by stomatal conductance, and an equilibrium component driven by the receipt of net radiation. The balance between these two components depends on the degree of coupling of leaves to atmosphere and is expressed by a dimensionless decoupling coefficient, the ‘omega factor’ (range 0 to 1.0): the sensitivity of transpiration to a fractional change in stomatal conductance depends on the size of the omega factor. Well-exposed, quite tall crops, like most orchard crops, are generally well-coupled to the atmosphere (small omega close to zero), with transpiration proceeding largely at the imposed rate. Only in these crops is transpiration likely to respond sensitively to small changes in stomatal conductance”. Jarvis (1985) points out that horticultural crops that are sheltered or growing in glasshouses are poorly-coupled to the atmosphere (omega close to 1.0) and their transpiration depends strongly on radiation receipt rather than changes in stomatal conductance.

Values of Ω increase with decreasing wind speed (Landsberg and Powell, 1973; Jarvis and McNaughton, 1986) which is one of the strongest microclimatic changes under netting. The canopy boundary layer is deepened (Tanny and Cohen, 2003) so that the saturation deficit within the canopy becomes more decoupled from the free air flow above. It would appear that whole tree transpiration in apple orchards under netting becomes less influenced by stomatal conductance and more influenced by radiant energy compared to open orchards. This would mean that canopy conductance could increase in response to the milder microclimate, but with a smaller increase in canopy transpiration than would be expected in the open. Thus, net CO_2 assimilation rate would increase relatively more than transpiration rate, giving rise to an increased orchard-level WUE (Nicolás et al., 2005; Alarcón et al., 2006). However, changes in soil irradiation and temperature are not yet factored into this equation – the evaporation component has not been studied and could alter the net outcome either positively or negatively.

Very few studies have quantified the water savings of apple production under protective netting compared to the open. When the two treatments have been irrigated separately on the basis of measured reference evapotranspiration, the water savings under netting amounted to around 25% in Spanish peaches (Girona et al., 2012) and 30% in Serbian apples (Prokopljević et al., 2012). Crété et al. (2001) (cited in Iglesias and Alegre, 2006) indicated that it is possible to reduce irrigation needs of apples by about 15% with respect to the control.

An unpublished three-year apple shade netting trial in Australia[3], with a similar climate to the Western Cape apple production region, reported on water savings achieved under white and black netting. With the conventional under tree irrigation system used in the first season, irrigation water

[3] https://www.agric.wa.gov.au/water-management/netted-apple-demonstration-final-summary?nopaging=1

applied was reduced from 6000 m^3 ha^{-1} outside the net to 5000 m^3 ha^{-1} under the net. After the conversion to drip irrigation in the second season, irrigation water applied was 2000 m^3 ha^{-1} outside the net and 1700 m^3 ha^{-1} under the net. Thus, a similar (ca. 15-17%) reduction in water use was achieved with netting, but a much larger reduction resulted from conversion to drip irrigation. The total water applied (irrigation plus rainfall) was reduced from 9420 m^3 ha^{-1} to 5780 m^3 ha^{-1}, a reduction of about 40% over the three year demonstration. Maintaining yield and fruit quality while reducing water used resulted in almost 300% improvement of irrigation WUE.

2.4.5 Bud development, flowering and fruit set

Orchard observations in South Africa have given rise to concerns that netting could decrease the fruitfulness of apple orchards over time. This may derive from the impact that protective netting (insufficient direct light, and/or competition between vegetative and reproductive growth) may have on the processes of reproductive bud development (RBD), flowering and fruit set (Tustin et al., 1992; Wünsche et al., 1996; Bepete and Lakso, 1998; Wünsche and Lakso, 2000; Do Amarante et al., 2011; Mupambi et al., 2018). If installed prior to bud burst or permanently, the effect of netting on flowering may already derive from the impact on RBD.

RBD processes include floral induction, initiation and differentiation, which collectively take place over two seasons (Bergh, 1985a; Greybe and Bergh, O., 1998; Hättasch et al., 2008; Koutinas et al., 2010). During induction a bud transitions either into a reproductive or a vegetative bud (Hättasch et al., 2008; Koutinas et al., 2010; Heide et al., 2020). Induction is followed by initiation, which is the process that results in the first sign of any histological changes (Bergh, 1985a; Hättasch et al., 2008; Koutinas et al., 2010) and is irreversible. Initiation is usually aligned with the cessation of shoot growth (Koutinas et al., 2010; Heide et al., 2020). The final process of RBD is differentiation, which spans the period after initiation until bloom the next season (Bergh, 1985a; Koutinas et al., 2010) and involves the gradual development of the king (first) and lateral flowers. Initially, the development of new whorls in the bud is rapid, but slows down before and during dormancy. Then, once endodormancy has ceased and anthesis approaches, differentiation of the various whorls accelerates (Bergh, 1985a; Koutinas et al., 2010).

RBD processes are regulated by a network of genetic pathways involved in vernalization, autonomy, photoperiod, and regulation through the plant hormone gibberellic acid (GA) (Zhang et al., 2019). However, photoperiod has been shown to have a minimal role in apple RBD processes. Early RBD processes of induction and initiation respond to a variety of environmental and internal cues that ultimately determine the reproductive or vegetative status of every bud. These cues include factors such as solar radiation (Solomakhin and Blanke, 2008, 2010a) and temperature, and crop load level and leaf area of the previous season (Wilkie et al., 2008).

Effects of radiation on the rate of bud differentiation could be explained by effects on the photosynthetic rate of local leaves associated with reproductive buds (Corelli-Grappadelli, 2003). In addition, high carbohydrate reserve levels have been suggested to be important to bud differentiation and RBP (Fernandez et al., 2020). If stored reserves and photosynthetic output are reduced, for example by the reduced light levels under protective netting, it is possible that RBP will be hindered. This may lead to delayed bud break and less provisioning of carbohydrates for subsequent growth.

A lower light transmission into the canopy may also lead to a reduction of leaf-level transpiration (Gindaba and Wand, 2007) and the whole tree transpiration stream. This may impede the delivery of growth-promotive hormones, such as cytokinin, via the transpiration stream from the roots to the shoots and buds (Lakso, 1994). These hormones are generally associated with an increased rate of floral initiation (Pitchers et al., 2021) and improved reproductive bud differentiation (Lakso, 1994). In addition, the lower light intensity under protective netting could increase shoot growth (Mupambi et al., 2018). Increased shoot growth is generally associated with an antagonistic interaction with reproductive growth and RBD (Jackson, 2003).

A successful apple harvest also requires effective pollination and fruit set (Dennis, 2003). This is influenced by several factors, including light (Corelli-Grappadelli, 2003; Boini et al., 2021). As protective netting has a significant influence on the canopy microclimate (Kalcsits et al., 2017), aspects of flower quality may be affected. Protective netting can have a significant effect on apple fruit set (Middleton and McWaters 2002; Shahak et al., 2004; Do Amarante et al., 2011). Pollination and fertilisation are the prerequisites for fruit set. Lower light levels may reduce fruit set through interference of bee activity and pollination. Concerns have been raised around pollination effectiveness and the ability of pollinating bees to work under the netting.

Following initial fruit set, continued development is influenced by several factors during the first 40 days after full bloom (DAFB). These include the hormonal balance and water status of the trees, crop load and seed count of the previous season, and competition dynamics between vegetative and reproductive sinks (Jackson, 2003). Alterations in temperature and light under netting can be important but variable effects have been reported (Mupambi et al., 2018). Temperatures in this period early fruit growth (Dennis, 2003; Jackson, 2003). Fruit set is decreased under low light (Rom, 1991) due to reduced photosynthetic activity and carbohydrate reserves (Dennis, 2003; Jackson, 2003).

The processes of RBD, especially differentiation, and any effects of the altered microclimate under protective netting on RBD, can also impact on fruit set (Do Amarante et al., 2011). The flowering period of apple trees has been reported to be protracted under shaded conditions (Pitchers et al., 2021) leading to unsynchronised flowering, poor pollination (Ramírez and Davenport, 2013) and reduced fruit set (Cook, 2007).

Due to the significant influence of protective netting on the microclimatic conditions of orchards (Kalcsits et al., 2017; Mupambi et al., 2018), this adaptive technology has the potential to impact negatively on year-on-year fruit set and yield. It is likely that these responses are highly dependent on changes in microclimate in individual situations, which vary depending on the type (density) and colour of the netting used, the cultivar, and the climate of the production area. There is a concern that yields of apple orchards under draped netting in South Africa are gradually declining (J. le Roux, personal communication 2018), linked to decreasing fruit size (P. Dall, personal communication 2018) and this may relate to sub-optimal crop load management (thinning not done properly once the net is already up). Crop load management has a considerable impact on the reproductive growth and yield of apple trees in the current and the following season (Wünsche et al., 2005). Thus, crop load management could be adjusted to possibly reduce the negative impact (Smit, 2007).

2.4.6 Yield, fruit maturity and fruit quality

From the perspective of absolute water savings achieved under protective netting in apple orchards, yield, fruit quality and return bloom are of minor significance. Dzikiti et al. (2018a) quantified apple orchard water use under various yields and found that yield is not a major determinant of water use, although WUE increases with increasing yield. Nevertheless, from a farm production and profitability perspective, achieving optimum yield and fruit quality are central to all decisions made. Furthermore, the need to increase WP in South African fruit production drives the focus towards water savings combined with high yield and income. We could not source any publications reporting on changes in either WP_p or WP_e in fruit orchards under and outside protective netting. Nevertheless, the literature on netting effects on yield and fruit quality is large. Mupambi et al. (2018) have summarised many of the main factors.

Yield and fruit quality together are the critical factors in determining profitability. The effects of protective netting on fruit quality are as wide-ranging as the various studies and their particular environmental and cultural characteristics. Mupambi et al. (2018) provided a comprehensive review of netting effects on apple fruit quality. Common effects of significance to South African apple production include a significant reduction in sunburn (Gindaba and Wand, 2005; Smit, 2007; Iglesias and Alegre, 2006; Brink et al., 2015; Kalcsits et al., 2017), reduced peel red colour development (Widmer, 2001; Stampar et al., 2001; Dussi et al., 2005; Gindaba and Wand, 2005; Smit, 2007; Solomakhin and Blanke, 2007; do Amarante et al., 2011; Brink et al., 2015), and reduced total soluble solids (Middleton and McWaters, 2002; Gindaba and Wand, 2005; Iglesias and Alegre, 2006; Smit, 2007; Solomakhin and Blanke, 2010b). These quality effects differ between white and black nets (Ordóñez et al., 2016). Several technologies, e.g. reflective mulch cloth (Extenday^{TM}) have been tested under netting to counter the negative effects on red colour (Blanke, 2008). Unpublished results from field trials in the EGVV area indicate significantly better green peel colour of 'Granny Smith' apples when grown under draped netting compared to the open, together with large reductions in sunburn and pink blush.

2.5 SUMMARY

The installation of shade netting over apple orchards is gaining momentum in South Africa and other parts of the world which experience very warm summers (e.g. Australia, Brazil, Washington State USA, Spain, eastern Europe), as the high costs are now more than offset by the benefits to fruit quality and profitability. Netting is already widely used in Europe and locally in the eastern Free State to protect the crop against hail damage, and the lessons learned in these regions have helped to guide the practice elsewhere. In this review we have discussed the fundamental changes in microclimate which occur under netting compared to the open, and how they influence physiological and growth responses of the apple tree from leaf to orchard level. We have focused on processes that determine leaf, tree and orchard water use since this is the overall objective of the research project. We also summarised the various approaches to measuring water use and which of these are best suited to application under netting, given the significant limitations posed by the physical barrier of the net.

The review shows how complex a comparison of water use under netting compared to the open is. Although the majority of the science suggests a high likelihood of water savings under netting, this is by no means a given. In a scenario of very vigorous vegetative growth, or a certain combination of changes in VPD_{leaf} and stomatal opening (and thus greater transpiration rate), or even one where diffuse radiation interception by interior and lower canopy leaves results in greater gas exchange of those leaves, it is possible that much smaller (or no) reductions in tree water use could result. Our review confirmed (surprisingly) how little field-based research has been conducted globally on changes in fruit tree and orchard water use under netting. Specifically, sap flow measurements in apple orchards under netting have not been reported in the scientific literature (although researchers in Western Australia used this technique but the results have not yet been published). No research has been conducted on the effects of netting on orchard floor evaporation or cover crop transpiration, which are important components of orchard evapotranspiration especially in younger orchards. Furthermore, no studies have calculated WP_p or WP_e of apple production with and without netting. It is critically important for the long term sustainability of the apple industry in South Africa to obtain this information so that planning of water allocations can proceed on the basis of facts.

Interviews with local technical experts and advisors confirms that they have very little scientific information on which to base decisions and advisory to clients. Much of the knowledge comes from informal farm trials and “learning by doing” but there is a great need for a better science-based understanding of apple production under netting. Therefore this project is timely and important from both the scientific and practical perspective.

CHAPTER 3: MATERIALS AND METHODS

3.1 STUDY SITES AND TRIAL DESCRIPTIONS

3.1.1 Fixed netting trial (Paardekloof, KBV)

As prescribed in the Term of Reference for the project, the open/fixed netted site was the Orchard of the Future at Paardekloof (KBV) (Figure 2). Paardekloof farm is situated in the Witzenberg valley less than 20 km to the north of the town of Ceres along the R303 to Citrusdal (33°15'40"S, 19°15'55"E, 900 masl). The orchard lies on the western foot slopes of a mountain (slope less than 5%), and has a deep sandy soil of the Fernwood form, with no stones. The orchard is planted to 'Rosy Glow' on MM109 rootstock with an M9 interstem (MM109/M9). 'Rosy Glow' is a late-season, high-coloured spontaneous single limb mutation of 'Cripps' Pink' which can also be marketed under the Pink Lady® brand when it meets the quality criteria, and is thought to give better fruit colour under less than optimal climatic conditions.

The orchard (1.05 ha) was planted in 2010 on ridges with a north-north-east – south-south-west orientation. Planting density was high (3.5 x 1.25 m), giving 2285 trees per hectare. The pollinator is 'Royal Gala' at 10%, i.e. every 10th tree in the row arranged as a diamond across rows. For the 2018-2019 season, bud break occurred around 26 September 2018, while the full-bloom date was around 9 October 2018 (Figure 3). Mean trunk circumference of the trial trees was 23.4 cm (range: 21.0-25.5 cm) at the start of the season (September 2018).

Figure 2 The trial site at Paardekloof (white fixed netting, 2018-2019 and 2019-2020) showing the two rows used under netting (blue) and in the open (red).

Figure 3 'Rosy Glow' apple trees under white shade netting or in the open on 19 January 2018 (left, fully developed canopy) and 9 October 2018 (right, full bloom). The dense grass ground cover can be seen in the left-hand photo.

In December 2014, the orchard was split into two sections and fixed shade netting with open sides installed over one section of 0.56 ha, with 0.49 ha remaining open (Figure 2). Two types of netting were installed at 4 m height. These included a knitted 40% crystal (0.30 ha) and knitted 20% white (0.26 ha), giving ca. 10-15% light reduction. In 2016, the irrigation system was split so that the netted and open sections are managed as separate irrigation blocks. We conducted the study only under the white netting due to better yield and fruit quality reported by the farm for this section compared to the section under crystal netting. The orchard was at full production and was high-yielding (114 t ha^{-1} in 2016/2017 under the white shade netting).

The micro-sprinkler irrigation system employs Gyros placed between two adjacent trees (Figure 4). Irrigation scheduling was decided on the basis of soil water content depletion using an AquaCheck system (AquaCheck, Cape Town, South Africa), together with one neutron probe, in different parts of the orchard. For the 2018-2019 season, irrigation commenced around mid-October. The ground cover between the tree rows (off-ridge) was a dense indigenous grass layer intermixed with various weed species which were mowed on occasion.

Irrigation water was drawn from the nearby farm dam which drew its water from mountain runoff and snow melt from the adjacent mountains. The dam was full at the start of the 2018-2019 season, and provided enough water even at the end of the 2017/2018 season at the height of the drought (Figure 5). Dam water quality was excellent and it was well within the irrigation water quality guidelines.

Figure 4 The orchard in the open on 21 September 2017 showing the ridges with mulch and Gyro micro-sprinklers between adjacent trees.

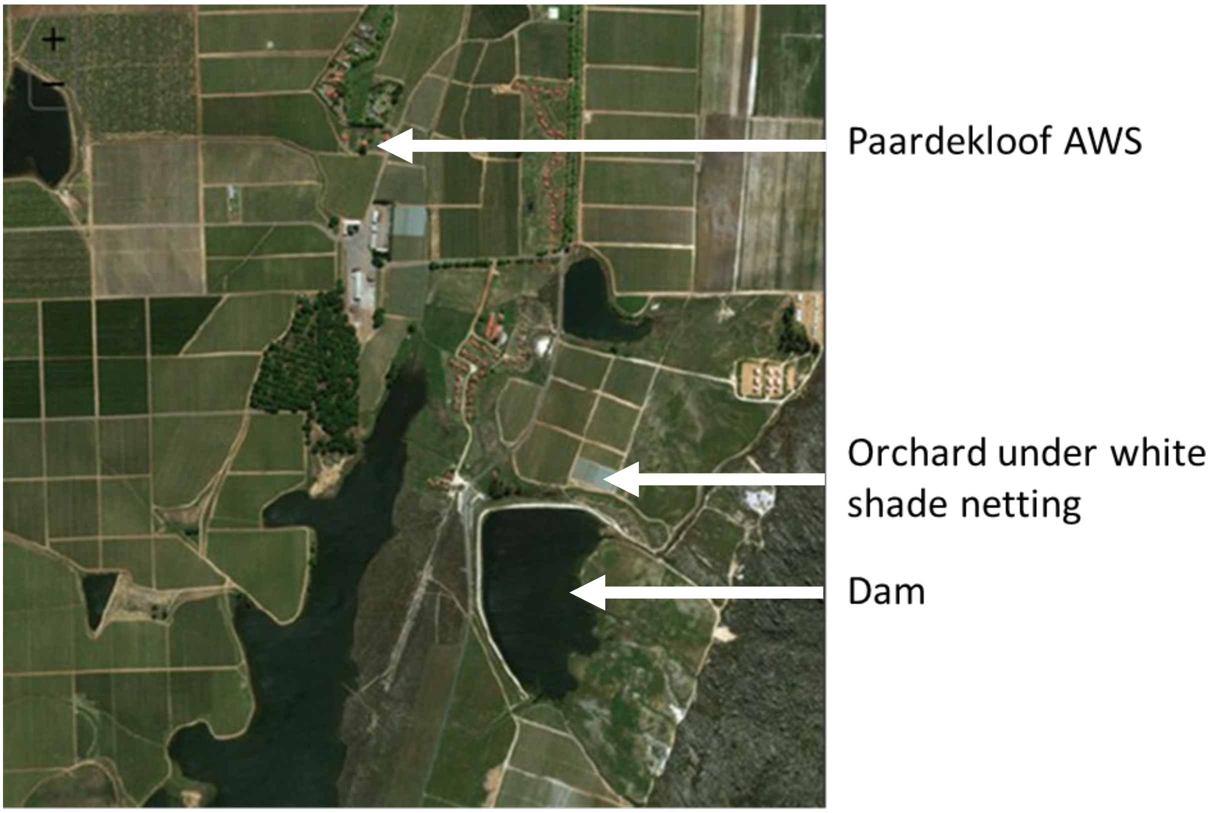


Figure 5 A lower resolution photo of the site at Paardekloof showing the dam which supplies irrigation water to the orchard, and the position of the ARC Paardekloof automatic weather station.

The orchards were managed according to standard best practice management principles employed by Paardekloof. Rest-breaking agents (Dormex/oil) were applied on 29 August 2018. Full bloom was recorded around 8 October 2018 and was followed by chemical thinning (Pomoxa/Sevin) on 15 October and shoot pruning/hand thinning on 21 November. The growth regulator Regalis® (active ingredient prohexadione-calcium) was applied to both orchards on 9 and 30 October. Fertilisation was done as recommended by the consultant in spring/early summer and post-harvest. Pest and disease control was done according to standard commercial practices. Commercial harvest took place in weeks 16-18 (April 2019). In June, compost was applied at 15 m^3 ha^{-1}, and a mulch of bark chips was placed on the ridge at 250 m^3 ha^{-1}.

In the open/fixed netting trial, the middle two rows were used in both the control and netted areas (Figure 2). Five trees in the middle of each row were chosen based on a representative range of trunk circumferences. Thus, there were two treatments with 10 single-tree replicates. The statistical analysis of all data was a T-test.

3.1.2 Draped netting trial (Paardekloof, KBV)

The position of the trial orchard is shown in Figure 6. The site had a slope of less than 5%, and deep sandy soil of the Fernwood form, with no or very few stones (

). The orchard was planted to 'Golden Delicious Reinders' on MM109 rootstock. 'Golden Delicious Reinders' is a mutation of 'Golden Delicious' which has a very low susceptibility to russetting. The orchard (Block W4) was 2.95 ha in size and was planted in 2009 on ridges with a north-south orientation. Planting density was 4.0 x 1.75 m, giving 1428 trees ha^{-1}. The pollinator was 'Royal Gala' at 12.5%, i.e. every 8th tree in the row arranged as a diamond across rows. Mean trunk circumference of 122 trees in the four trial rows was 32.7 cm and that of the twenty trial trees was also 32.7 cm (range: 23.6-37.3 cm) at the start of the season (3 September 2019). The orchard was at full production – on average 105 t ha^{-1} from 2017 to 2019.

For the 2019-2020 season, rest-breaking sprays were applied on 5 September 2019 (green point date) using 1% Deurbraak (hydrogen cyanamide) + 4% Cipron Oil. The full-bloom date was 2 October 2019. Chemical thinning sprays were applied on 21 October 2019 using 500 ml Maxcel (6-benzyladenine) + 10g Regulex (gibberellins A4 + A7) in 100 ml water. Hand thinning was performed on 27 November 2019. No summer pruning was done. Fertilisation was done as recommended by the consultant in spring/early summer and post-harvest. Pest and disease control was done according to standard commercial practices. The commercial harvest took place in week 9 (24-28 February 2020) with the net being removed on 26 February.

In October 2019, the microsprinkler irrigation system was split so that the netted and open sections were managed as separate irrigation blocks (Figure 8). The system employed Gyros placed between two adjacent trees. Irrigation scheduling was decided on the basis of soil water content depletion using an AquaCheck system (AquaCheck, Cape Town, South Africa), together with neutron probes, in different parts of the orchard. Since the existing AquaCheck sensor was situated in what was now close to the control (no net) treatment rows, an additional AquaCheck sensor was installed in the netted section to facilitate separate irrigation scheduling. Irrigation commenced on 4 October 2019. The ground cover between the tree rows (off-ridge) had a dense indigenous grass layer intermixed with various weed species which were mowed on occasion. No mulches or compost were applied in the 2018-2019 season.

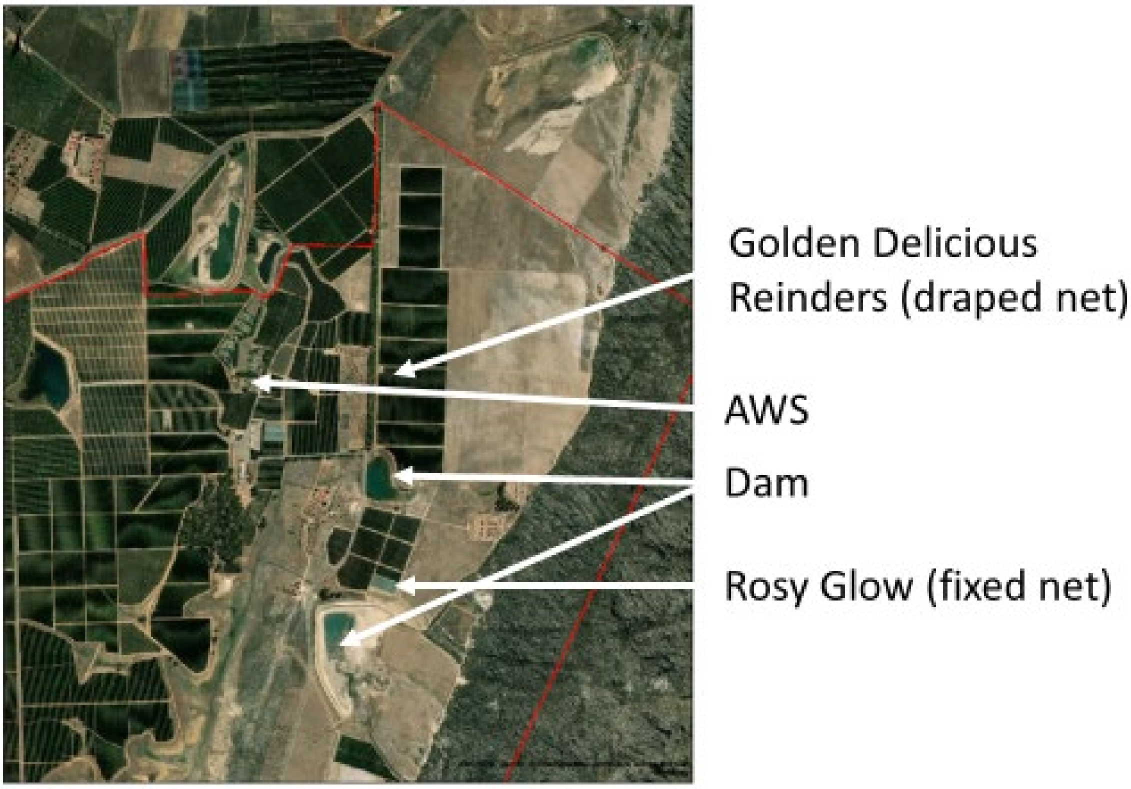


Figure 6 Aerial view of Paardekloof farm showing the position of the two trial orchards, the two dams which supply irrigation water to the orchards, and the position of the ARC Paardekloof Automatic Weather Station (AWS). The 'Golden Delicious Reinders' orchard is the site for the first trial on quantifying the effects of draped nets on apple water use. The 'Rosy Glow' fixed net orchard is in its second trial season.

Figure 7 'Golden Delicious Reinders' orchard in September 2019 showing ridges, tractor track, cover crop and sandy soil.

Figure 8 ‘Golden Delicious Reinders’ orchard in January 2020 showing the separate irrigation system installed for the four draped net rows.

The black draped nets were installed over the four rows of the netted area on 27 November 2019. This was timed to occur as soon as possible after hand thinning which was completed on the same day before the installation. The nets were not tied around the trunks but were left to hang loosely at a height of ca. 1 meter above-ground (Figure 9). This was low enough to ensure coverage of almost all the lower branches. The product Drape Net® was supplied and sponsored by the Nulandis Regional Office. It is a UV stabilised 100% virgin High Density Polyethylene with a mesh size of 6 mm x 1.8 mm (Figure 10) and a unit mass of 60 g m^{-2}. The screening factor was given as 24%.

Figure 9 ‘Golden Delicious Reinders’ rows covered in draped netting, January 2020.

Figure 10 Close-up view of the black draped netting structure showing the 6 mm x 1.8 mm mesh size.

In the draped net trial, the middle two rows are used for measurements in a four-row block (0.18 ha) for each of the control and netted areas which were situated adjacent to one another on the same side of the road (Figure 11, Figure 12). Five trees spread across the middle section of each row were chosen based on a representative range of trunk circumferences and a mean trunk circumference close to the mean of the two rows used per treatment. Thus, there were two treatments with 10 single-tree replicates. The statistical analysis of all data was a T-test.

Figure 11 Position of the eight rows used in the 'Golden Delicious Reinders' block at Paardekloof.

Figure 12 'Golden Delicious Reinders' netted and adjacent open (control) rows.

3.1.3 Draped netting trial (Southfield, EGVV)

The second draped nets trial was established in a mature 'Golden Delicious' orchard at Southfield Farm (33°58’15.84” S; 19°18’31.14” E; 377 masl), about 2 km north of the town of Villiersdorp (Figure 13). The specific orchard used is Block B5 (Figure 14). The orchard is very gently sloping in an east-west direction, and has deep sandy loam soils, with no or very few stones. The soils are described in more detail later in this report.

Figure 13 Location of the draped net trial on 'Golden Delicious' apples at Southfield farm. The location of Villiersdorp town and the site of the third automatic weather station is also indicated.

Figure 14 Location of the 'Golden Delicious' trial orchard (Block B5) on Southfield farm.

The orchard was planted in 1987 (thus 33 years old) on M793 rootstock at a spacing of 4 m x 2 m, giving 1250 trees/ha. The pollinator is 'Granny Smith'. Prior to the drought in 2015-2018, the orchard was consistently producing yields of more than 100 t ha^{-1}, except in years following heavy pruning when yield was somewhat lower. The drought had a negative impact on yield and the trees were heavily pruned to stimulate their recovery. The yield in 2019-2020 was 65 t ha^{-1}, and the bearing positions had recovered well when this trial commenced. The orchard yields fruit of very high quality. The orchard was irrigated using a microsprinkler irrigation system, with jets (40 L/hr) positioned between two adjacent trees (Figure 15). The netted and open sections were managed as one irrigation block. The orchard floor comprises of rye grass as a cover crop while the area underneath the canopies was kept free of plants. No mulches were applied during the course of the study. There was no security at the farm, but the equipment was placed in locked strongboxes, placed underground, or otherwise hidden from plain sight. It was not visible from the nearby public road. Cell phone reception was good and there was excellent cooperation from the farm management.

The full-bloom date was 21 October 2020. No chemical thinning sprays were applied since there was significant natural fruit drop owing to the weather conditions during the bloom period. Very light hand thinning was performed on the trial rows on 8 December 2020.

Figure 15 View of a microsprinkler jet positioned between two adjacent trees.

The black draped nets (re-used from the 2019-2020 trial) were installed over the middle two rows of the netted area on 17 December 2020, for the first 50 trees in the row. This was timed to occur as soon as possible after hand thinning (8 December) and at the advice of the net supplier based on fruit size (Figure 16) and climatic risks. Due to a misunderstanding, the middle two rows of the control area were also covered in draped nets on 17 December. This was rectified on 24 December, as soon as possible after we became aware of the error. The nets were taken down and installed over the outer two rows of the netted area. The nets were installed manually (Figure 17). Care was taken when covering the draped net automatic weather station (Figure 18). The bottom of the net covered most of the low-lying leaves (Figure 19), and was tied around the trunks since this area can receive strong south-easterly winds in summer.

The product Drape Net® was supplied and sponsored by the Nulandis Regional Office. It is a UV stabilised 100% virgin High Density Polyethylene with a mesh size of 6.0 mm x 1.8 mm and a unit mass of 60 g m^{-2} (Figure 20). The screening factor was given as 24%.

Figure 16 Size of the apple fruit on the day of draped net installation (17 December 2020).

Figure 17 The nets were installed manually.

Figure 18 Draped net being pulled carefully over the draped net site automatic weather station.

Figure 19 Draped net pulled down, showing height above ground level, before it was tied around the trunks.

Figure 20 Close-up of the black High Density Polyethylene net with a mesh size of 6.0 mm x 1.8 mm.

In the draped net trial at Southfield, the middle two rows were used for measurements in a four-row block for each of the control and netted areas which were situated adjacent to one another on the same side of the road (Figure 21). Five trees were chosen in each row based on a representative range of trunk circumferences and a mean trunk circumference close to the mean of the two rows used per treatment. Mean trunk circumference of the ten control trees in September 2020 was 49.6 cm, and that of the ten netted trees was 50.7 cm. Four of the ten trees per treatment were instrumented for sap flow measurements (control mean: 49.3 cm; net mean: 49.7 cm) and two of the ten trees were instrumented for soil water balance analysis (control mean: 54.6 cm; net mean: 51.6 cm). Thus, there were two treatments with 10 single-tree replicates, but four replicates for sap flow and 2 replicates for soil water balance (SWB). The statistical analysis of all data was a T-test.

Figure 21 Position of the eight rows used in the 'Golden Delicious' block at Southfield. In each treatment (4 rows) the middle 2 rows are used for measurements and monitoring.

3.2 ORCHARD MICROCLIMATE

3.2.1 Fixed netting trial (Paardekloof, KBV, 2018-2019)

To investigate the key drivers of water use and orchard productivity, weather conditions were accurately measured using automatic weather stations (AWSs). One AWS was located in the open unshaded orchard and the other under the shade netting. Additional weather data were also obtained from a third standard AWS installed in an open space with a uniform grass cover. At Paardekloof (2018-2019 and 2019-2020) these data were obtained from an ARC-managed AWS situated in the open space next to the estate offices less than 1.5 km from the study orchard (Figure 22). These stations facilitated the calculation of the atmospheric evaporative demand, depicted by the reference evapotranspiration (ET_o) for a short grass using the FAO Penman-Monteith equation (Allen et al., 1998).

Figure 22. ARC automatic weather station at Paardekloof farm.

At the start of the first season (October 2018), two AWSs which were to be installed in the orchards at Paardekloof were calibrated against one another in an adjacent open field before placement in the orchards (Figure 23). This was done to eliminate systematic errors due to differences in sensor readings. All the sensors were mounted on a tripod which was placed securely in the tree row (Figure 24, Figure 25). Each station comprised a digital thermopile pyranometer (Model: CS320, Campbell Scientific, Inc., Logan, UT, USA) to measure the solar irradiance at a height just above the canopy (ca. 3.4 m above the ground, 0.6 m under the netting in the case of the netted block). This is a dome-shaped pyranometer that is suited to measurement under netting, according to Prof Mike Savage (N. Taylor, pers. comm., 17 July 2018). This is because its sensor eliminates spectral errors associated with silicon-cell pyranometers (https://www.campbellsci.co.za/cs320). Each pyranometer was installed on a leveling plate installed on a north-facing cross bar to prevent self-shading by the sensor. Air temperature and relative humidity were measured using a digital probe (Model: CS215, Campbell Scientific, Inc., Logan, UT, USA) installed inside a radiation shield to eliminate radiation errors at ca. 2.0 m above the ground.

Figure 23. Cross calibration of the two automatic weather stations to establish systematic errors among the sensors prior to the 2018-2019 season.

Sonic anemometers (Model: ATMOS-22, METER Group, Pullman, WA, USA) were used to measure wind speed and direction. This model is highly suited to low wind speeds as expected under netting, and has no moving parts (ideal for under draped netting for the next season). Under the netting, one anemometer was installed at a height of 3.4 m (top of the tree), and a second anemometer was installed at ca. 2.0 m above the ground, in the middle section of the canopy and protruding 0.3 m into the alley in an open part of the canopy (Figure 24). In the open site, one anemometer was installed at ca. 2.0 m above the ground protruding 0.3 m into the alley.

Rain data was obtained from the Paardekloof AWS (Figure 22) (and not the rain gauge installed at the site, Figure 24). The effective rainfall on the orchard floor was calculated from the gross rainfall measured at the outside station and the orchard leaf area index (LAI). All the sensors for the open orchard were connected to a Campbell Scientific CR1000 data logger programmed with a scan interval of 10 s. The output signals were processed at hourly and daily intervals. Weather sensors under the netting were connected to a CR3000 Campbell Scientific data logger with an identical program to the logger in the open. Power to each station was supplied by an 12 Ah battery stored in the data logger enclosure. However, logger malfunctioning due to a spent internal battery in the CR3000 led to loss of data for the first two weeks in the 2018-2019 season.

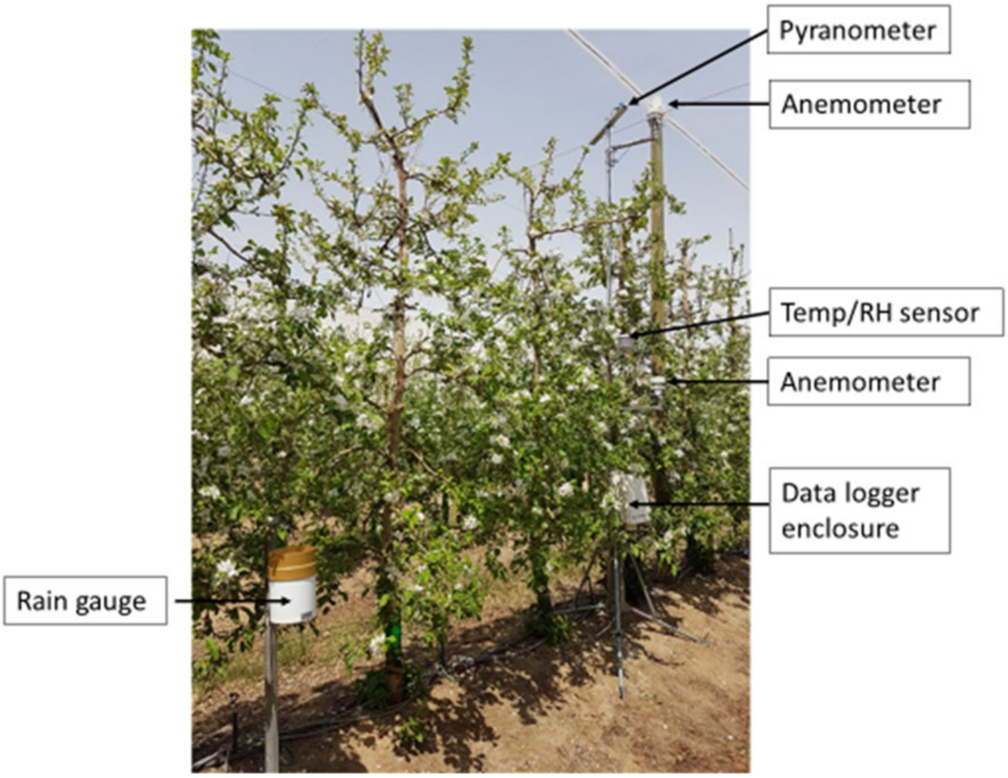


Figure 24 Automatic weather station measuring basic weather elements in the orchard under fixed white shade netting.

Figure 25 Automatic weather station measuring basic weather elements in the open orchard. Installation is being conducted by the PhDAgric student, Mr Edward Lulane, on 9 October 2018 (full bloom).

3.2.2 Fixed and draped netting trials (Paardekloof, KBV, 2019-2020)

Weather data were collected using three automatic weather stations installed at the fixed and draped netting sites. The same variables as described in section 3.2.1 were measured using the same sensor models. Rainfall data was obtained from the Paardekloof AWS (Figure 22).

Prior to the start of the season, from 20-30 September 2019, the three stations were set up side by side in an open field with sensors installed at the same heights above the ground (Figure 26). The stations included those used for the 'Rosy Glow' fixed net and control orchards (data had been collected in these orchards since October 2018) and a new station for the 'Golden Delicious Reinders' draped net site, using exactly the same sensor models. This exercise was necessary to establish if there were systematic differences in the sensor readings that would bias interpretations of the effects of the shade nets on the orchards' microclimate. The only assumption in this study is that microclimate measurements in the 'Rosy Glow' control would be similar to those in the 'Golden Delicious Reinders' control in a similar environment. This assumption was necessitated by the high cost of purchasing a new weather station and the associated running costs. The AWS at the Paardekloof farm office managed by the ARC was used as an additional source of control weather data.

On 3 October 2019 the fixed net trial stations were re-positioned in the orchards as previously, and the new station was positioned in the draped net section of the draped net trial (Figure 27) which was still open.

Figure 26. Positioning of the three Automatic Weather Stations for the cross-calibration exercise in September 2019.

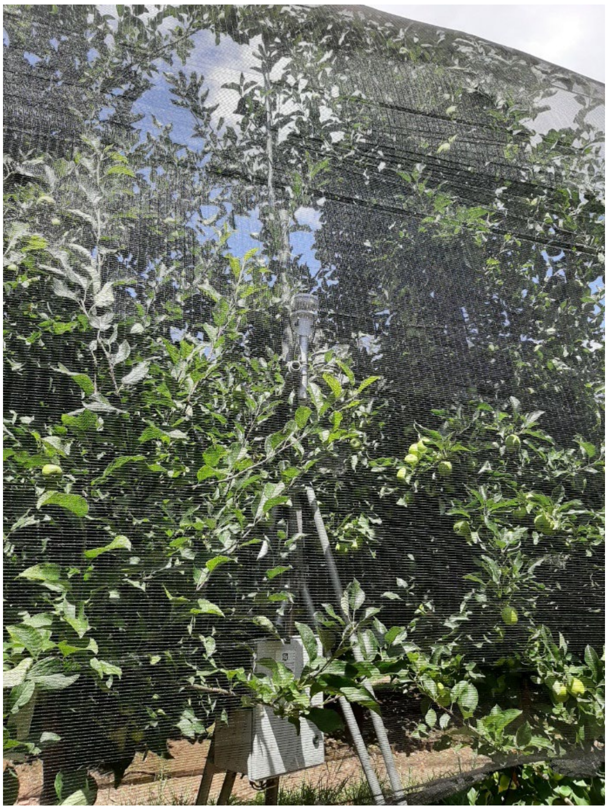


Figure 27. Automatic weather station installed under the draped netting in the 'Golden Delicious Reinders' orchard.

3.2.3 Draped netting trial (Southfield, EGVV, 2020-2021)

Weather data were collected using three automatic weather stations (Figure 28). One station was on a standard short grass reference site in the open (Figure 28a), located in front of the Vilko hardware store in Villiersdorp about 2.0 km from the study site (34°59'07.15"S; 19°17'47.58"E, 362 masl). The grass was irrigated and mown. The station provided rainfall data, and standard weather data for comparison with the in-field stations and also with other surrounding weather stations if needed. The second was in an open unshaded tree row (Figure 28b), and the third was in the tree row under the draped nets (Figure 28c). The same sensors were used as those for the trials at Paardekloof. The pyranometers were mounted above the canopy approximately 3.6 m height for the two infield stations facing northwards to avoid self-shading. The probes measuring air temperature and relative humidity, and wind speed and direction, were installed at a standard 2.0 m height in all three weather stations. All the sensors for each weather station were connected to a Campbell Scientific data logger programmed with a scan interval of 10 s, and all signals were processed every hour. Power to each station was supplied by a 12 Ah battery stored in the data logger enclosure.

Prior to the start of the season, from 25 September to 5 October 2020, the three AWSs were set up side by side in an open, uniformly grassed area (the Vilko site), with sensors installed at the same heights above the ground, to establish whether there were any systematic differences in sensor readings under similar exposures. This would bias interpretations of the effects of the shade netting on orchard microclimate. No meaningful differences were found and results are shown in Appendix D.

At the end of September 2020, two of the three stations were transported to Southfield and set up in the 'Golden Delicious' trial orchard, one each in the control and netted treatment rows. The stations were placed securely in gaps (where trees had died, thus being exposed to the sun) within the tree row. The third station remained at the Vilko site. Since the netted treatment rows were still open, we expected the two in-orchard stations to give highly similar readings from the start of monitoring on 1 October 2020 until the installation of the draped nets on 17 December 2020. This was carefully checked. Minor adjustments were made during data analysis to ensure that baseline readings were similar before the nets were installed.

Figure 28. Automatic weather stations measuring basic weather elements: Left: at the Vilko hardware store site just outside Villiersdorp, about 2 km from the orchard; Middle: in the control treatment rows of the study orchard; Right: under the draped netting in the study orchard.

3.2.4 Interception of photosynthetically active radiation: AccuPAR

Many studies have demonstrated that the intercepted radiation has a significant effect on tree water use and productivity in apple orchards. The presence of shade nets significantly affects the radiation microclimate around the trees, but little is known about the impacts on the intercepted radiation under South African conditions. Thus, experiments were conducted to quantify the intercepted photosynthetically active radiation (PAR) under each shade net type. Models of soil evaporation and tree transpiration require estimates of canopy radiation interception. Fractional interception of photosynthetically active radiation (fIPAR) in the fixed nets trial at Paardekloof was measured with a Decagon AccuPAR LP-80 ceptometer (Decagon Devices, Pullman, WA, USA) in a grid pattern at ground level around one representative tree in each treatment (Figure 29). Readings were taken manually on either side of solar noon in continuous cycles. At the start and end of each cycle, full sun (clear sky) readings were taken. Each grid reading was divided by the mean of the two full sun readings to give the fraction of PAR received at that position. Measurements were conducted on 26 October and 9 November 2018.

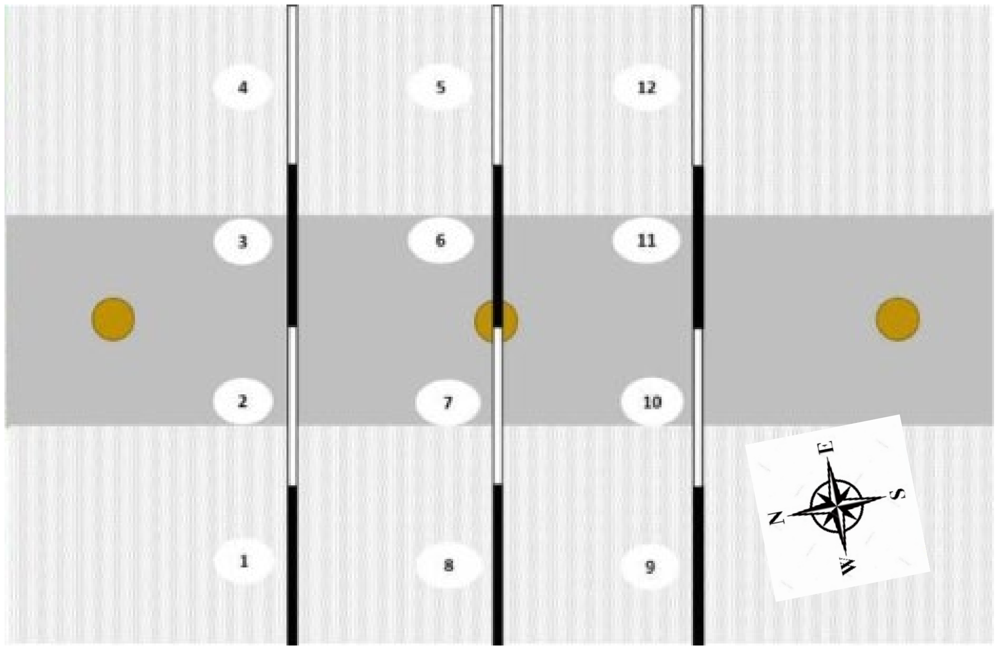


Figure 29 Grid for ceptometer PAR measurements in the shaded and open orchards. Orange circles indicate tree trunks. The row orientation is north-north-west by south-south-east.

3.2.5 Interception of photosynthetically active radiation: line quantum sensors

Detailed continuous radiation interception data under the fixed and draped netting was collected using the line quantum sensors (Model: LI-191R, Li-Cor, Lincoln, Nebraska, USA) during two field campaigns at Paardekloof (Figure 30). Each device has 10 PAR sensors equally spaced along a 1.0 m long rod. The two treatments (i.e. fixed and draped nets) could not be monitored at the same time due to equipment constraints. The first campaign was from 19 December 2019 to 15 January 2020. The sensors were left in the field until 27 January 2020. The campaign was repeated from 28 to 31 January 2020 on the draped nets site. The photosynthetically active radiation (PAR) was measured hourly throughout these periods.

Figure 30 Placement of the quantum line sensors to measure the intercepted PAR radiation at different levels in the 'Rosy Glow' canopy (fixed net) and the 'Golden Delicious Reinders' canopy (draped net).

3.3 SOIL PROPERTIES, SOIL WATER CONTENT AND IRRIGATION

3.3.1 Fixed netting trials (Paardekloof, KBV)

3.3.1.1 Soil physical properties

Soil samples were taken at Paardekloof on 20 December 2018 at six positions representative of the open (control) and netted areas, respectively, and pooled for five fraction particle size analyses (PSA) at a commercial laboratory. Samples were taken midway between two trees 300 mm perpendicular to the tree row. The sampling depth increments were 0-300 mm, 300-600 mm, 600-900 mm and 900 mm to 1.2 m. To determine soil water retention properties, tensiometers were placed at three representative experimental trees in the open and netted sections, respectively (Figure 31). Manual tensiometers were placed perpendicular to the centre of the tree trunk in the tree row. Tensiometers were installed at 300, 600 and 900 mm depths. Gravimetric soil water content samples were taken to obtain samples for a range of soil matric potentials at selected soil depths to determine soil water characteristic curves *in situ* in the open section and below net. Soil matric potential was read from tensiometers.

Figure 31 Tensiometers installed in the centre of the ridge between the tree stem and microsprinkler at 300, 600 and 900 mm depths in sandy soil in the 'Rosy Glow' orchard at Paardekloof in 2018.

Soil bulk density (P_b) values were determined *in situ* according to the core method (Blake and Hartge, 1986) in a row adjacent to the experimental rows in the open section and below net. Measurements were done at 200 mm, 600 mm and at 1 m and 1.3/ 1.4 m depths in the slope of the ridge, as well as at 200 mm, 600 mm and 1 m in the tractor track and middle of the work row, respectively.

3.3.1.2 Soil water content dynamics and soil temperature

In December 2018, ten soil water content sensors were installed at two experimental trees each in the open (C4, C10) and below net (N4, N8). The installations represent soil water conditions in the ridge and in the work row areas east-south-east (experimental tree 1) and west-north-west (experimental tree 2) of the ridge. The soil water monitoring equipment were connected to a CR1000 logger. The logging equipment and a 12 V 7Ah lead acid battery power supply were enclosed in a weather proof box. The CS650 and/or CS616 sensors (Campbell Scientific Inc., Logan, UT, USA) (length of probe head – 85 mm, rods – 300 mm, nonflexible cable – 40 mm) were installed horizontally at selected depths at three measurement positions in the soil which represents both the tree row and work row areas (Figure 32, Appendix E: Figure 137, Figure 138).

Figure 32 Installation positions of CS650 and/ or CS616 sensors in sandy soil in the 'Rosy Glow' orchard at Paardekloof in 2018-2019. The rods of sensors installed across the ridge are centred on the middle of the tractor track and cover crop sensor rods. Yellow lines and labels indicate the positions of the sensors below ground.

Three soil profiles per tree (Figure 33) included one midway between a microsprinkler and the tree in the tree row with sensors orientated across the c. 333 mm high ridge, one in the tractor track and one in the cover crop, each with sensors parallel to the tree row with the middle of the sensor prongs centred on the sensor rods in the centre of the ridge. Tree roots extended in the centre of the ridge in some cases up to a depth of c. 1.3 m, and cover crop and tree roots in the work row up to between 600 mm and 1 m. Soil water content sensors were installed in the root zone at 0.2, 0.6 and 1 m from the soil surface and in the ridge below the root zone at the 1.3 or 1.4 m soil depth (Figure 33). Soil water content could not be measured below the root zone in the work row due to limited equipment. To facilitate *in situ* calibration of the CS650/ CS616 probes at each experimental tree gravimetric soil samples were taken for a range of soil water contents at each installation depth. Soil temperature was monitored using the CS650 probes at 200 mm depth in the ridge, tractor track and cover crop.

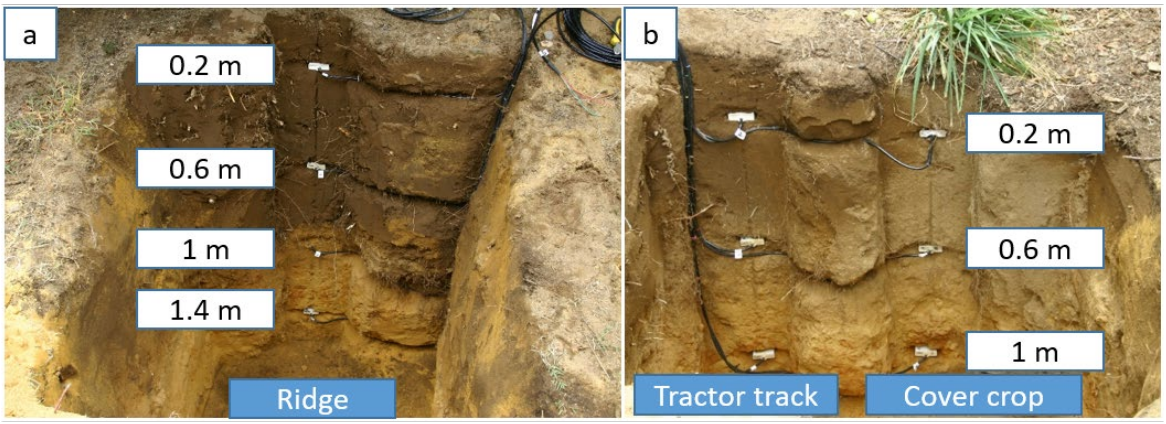


Figure 33 Soil water balance equipment installed in (a) the ridge and (b) the tractor track and cover crop in sandy soil in a ridged 'Rosy Glow' orchard at Paardekloof in 2018-2019. The installation depths of the CS650 and/ or CS616 sensors in the ridge, tractor track and work row area with cover crop are indicated.

3.3.1.3 Irrigation

Irrigation applied was monitored using electronic water flow meters with a resolution of 10 litres per pulse or better installed on the irrigation lines of one soil water balance replicate per treatment (Figure 34). In addition irrigation volumes applied were monitored in two adjacent irrigation lines using manual water flow meters read less frequently during the season. The amount of irrigation received by each tree was calculated as the ratio of the volume of water that passes through the flow meter divided by the number of microsprinklers downstream of the flow meter.

Figure 34 Electronic irrigation flow meter installed in the 'Rosy Glow' fixed netting trial.

3.3.2 Draped netting trial (Paardekloof, KBV)

3.3.2.1 Soil physical properties

Soil samples were taken at Paardekloof Block W4 on 27 November 2019 at ten positions representative of the open (control) and netted areas, respectively, and pooled for five fraction particle size analyses (PSA) at a commercial laboratory. Samples were taken midway between two trees c. 300 mm perpendicular to the tree row. The sampling depth increments were 0-300 mm, 300-600 mm, 600-900 mm and 900 mm to 1.2 m. To determine *soil water retention properties*, tensiometers were placed at three representative experimental trees in the open and netted sections, respectively. Manual tensiometers were placed perpendicular to the centre of the tree trunk in the tree row. Tensiometers were installed at 300, 600 and 900 mm depths. Gravimetric soil water content samples were taken to obtain samples for a range of soil matric potentials at selected soil depths to determine soil water characteristic curves *in situ* in the open section and below net. Soil matric potential was read from tensiometers. Soil bulk density (P_b) values were determined *in situ* according to the core method (Blake and Hartge, 1986) in a row adjacent to the experimental rows in the open and draped net sections respectively. Measurements were done at 200 mm, 600 mm and at 1 m and 1.3 m depths in the slope of the ridge, as well as at 200 mm, 600 mm and 1 m at representative positions in the tractor track and work row, respectively.

3.3.2.2 Soil water content dynamics

In September 2019, ten soil water content sensors were installed at two experimental trees each in the open (Control row 1, tree 22; Control row 2 tree 43) and below net (Draped net row 1, tree 21, Draped net row 2, tree 33). The installations at experimental tree 1 and 2 represent soil water conditions in the ridge and in the work row areas for opposite sides of the ridge. The soil water monitoring equipment were connected to a CR1000 logger. The logging equipment and a 12 V 7Ah lead acid battery power supply were enclosed in a weather proof box. The CS616 sensors (length of probe head – 85 mm, rods – 300 mm, nonflexible cable – 40 mm) were installed horizontally at selected depths at three measurement positions in the soil which represents both the tree row and work row areas (Figure 35).

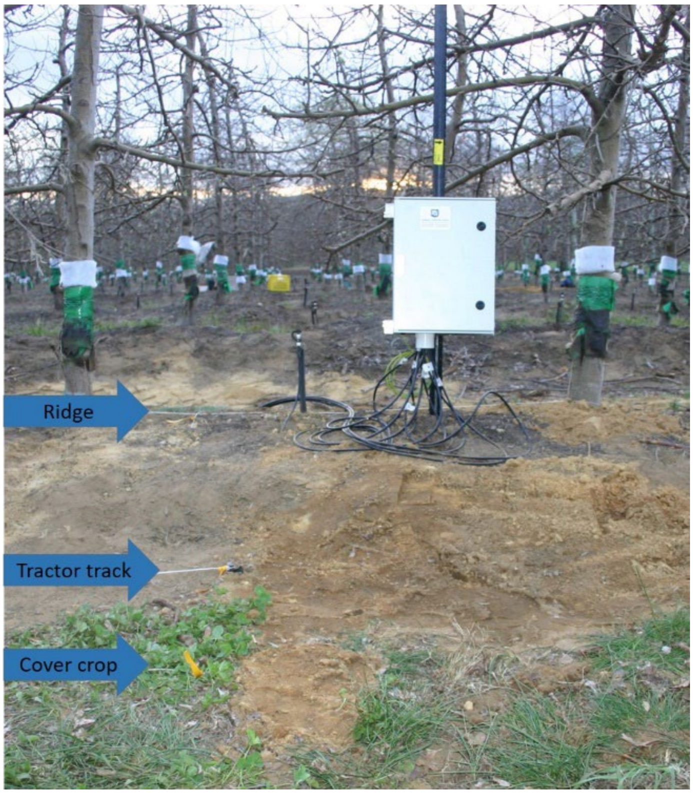


Figure 35 Installation positions of CS616 sensors in sandy soil in the draped net 'Golden Delicious Reinders' orchard at Paardekloof in 2019-2020. The rods of sensors installed across the ridge are centred on the middle of the tractor track and cover crop sensor rods. Yellow labels and white ropes indicate the positions of the sensors below ground.

Three soil profiles per tree included one midway between a microsprinkler and the tree in the tree row with sensors orientated across the c. 331 (±46) mm high ridge, one in the tractor track and one in the cover crop, each with sensors parallel to the tree row with the middle of the sensor prongs centred on the sensor rods in the centre of the ridge. Tree roots extended in the centre of the ridge in some cases up to a depth of c. 1.4 m, and cover crop and tree roots in the work row up to between 600 mm and 1 m. Soil water content sensors were installed in the root zone at 0.2, 0.6 and 1 m from the soil surface and in the ridge below the root zone at the 1.3 or 1.4 m soil depth (Figure 36).

Figure 36 Soil water balance equipment installed in (a) the ridge and (b) the cover crop and tractor track in sandy soil in a ridged 'Golden Delicious Reinders' orchard at the draped net site at Paardekloof in 2019-2020. The installation depths of the CS616 sensors are indicated.

Thermocouples were installed in December 2019 at representative positions at the 0.2 m depth to measure soil temperature. Soil water content cannot be measured below the root zone in the work row due to limited equipment. To facilitate in situ calibration of the CS616 probes at each experimental tree gravimetric soil samples was taken for a range of soil water contents at each installation depth.

3.3.2.3 Irrigation

Irrigation applied was monitored using a similar approach to that for the fixed net trial (see section 3.3.1.3.).

3.3.3 Draped netting trial (Southfield, EGVV)

3.3.3.1 Soil physical properties

Soil samples were taken at Southfield on 3 November 2020 at ten positions representative of the open (control) and netted areas, respectively, and pooled for five fraction particle size analyses (PSA) at a commercial laboratory. Samples were taken midway between two trees 300 mm perpendicular to the tree row. The sampling depth increments were 0-300 mm, 300-600 mm, 600-900 mm and 900 mm to 1.2 m. To determine *soil water retention properties*, tensiometers were placed at three representative trees in a border row of the open and netted sections, respectively. Manual tensiometers were placed perpendicular to the centre of the tree trunk in the tree row. Tensiometers were installed at 300, 600 and 900 mm depths. Gravimetric soil water content samples were taken to obtain samples for a range of soil matric potentials at selected soil depths to determine soil water characteristic curves *in situ* in the open section and below net. Soil matric potential was read from tensiometers.

Soil bulk density (P_b) values were determined *in situ* according to the core method (Blake & Hartge, 1986) in a row adjacent to the experimental rows in the open and draped net sections. Measurements were done at 150 mm, 450 mm, 750 mm, 1.05 m and 1.3 m depths in the centre tree row, tractor track and cover crop areas.

3.3.3.2 Soil water content dynamics

In September 2020, fifteen soil water content sensors were installed at two experimental trees each in the open and the draped net sections. The installations represent soil water conditions in the centre tree row and in the work row areas south (experimental tree 1) and north (experimental tree 2) of the tree row. The soil water monitoring equipment was connected to a CR1000 data logger (Campbell Scientific, Inc., Logan, UT, USA). The logging equipment and a 12 V 7Ah lead acid battery power supply were enclosed in a weather proof box. The CS650 and/or CS616 sensors (Campbell Scientific, Inc., Logan, UT, USA) have a probe head length of 85 mm, a rod length of 300 mm, and a nonflexible cable of 40 mm length. They were installed horizontally at selected depths at three measurement positions in the soil which represents both the tree row and work row areas (Figure 37, Figure 38). Three soil profiles per tree included one midway between a microsprinkler and the tree in the tree row, with sensors orientated across the tree row, one in the tractor track, and one in the cover crop, each with sensors parallel to the tree row. Soil water content sensors were installed in the root zone at 0.15, 0.45, 0.75, 1.05 and 1.3 m from the soil surface (Figure 38a, Figure 38b). To facilitate *in situ* calibration of the CS650/CS616 probes at each experimental tree, gravimetric soil samples were taken for a range of soil water contents at each installation depth.

Figure 37. Installation positions of CS650/CS616 sensors in sandy soil in the 'Golden Delicious' orchard at Southfield in 2020-2021. White rope and yellow labels on the soil surface indicate the relative positions of the sensors.

Figure 38. Soil water balance equipment installed in (a) the tree row and (b) the work row with cover crop and tractor track in sandy loam soil in a 'Golden Delicious' orchard at Southfield in 2020-2021. The installation depths of the CS650 and/ or CS616 sensors in the tree row, cover crop and tractor track area are indicated in (a).

3.3.3.3 Irrigation

Irrigation volumes applied by between 50 and 52 microsprinklers per orchard row were measured hourly for the control (orchard rows 4 and 5) and draped net (rows 7 and 8), each using a logging water flow meter connected to a CR1000 logger. The amount of irrigation received by each tree was calculated as the ratio of the volume of water that passes through the flow meter divided by the number of microsprinklers downstream of the flow meter.

3.4 TREE GROWTH AND LEAF AREA INDEX

3.4.1 Seasonal shoot and stem growth

At all three study sites, the length of two tagged extension shoots per tree (one on each side of the tree row: east and west) was measured from the end of October or early November, until mid-March (2019) or early February (2020, 2021). The shoots were on the outer canopy at approximately shoulder height. The measurements were generally performed once per month. The daily shoot growth rate, in mm growth per day since the first measurement date, was calculated.

Stem growth was monitored in 2018-2019 at hourly intervals using dendrometers (Model: DEX 100, Dynamax Houston, USA). Two trees were instrumented per treatment.

3.4.2 Canopy size and leaf area index

In October 2018 (fixed net site), canopy dimensions, namely the height and width (within and across rows) were measured. This was not done at the draped net sites.

The leaf area index (LAI) represents the size (m^2) of the one sided leaf area projected on a square meter (m^2) of ground area. The LAI was measured during each trial using an LAI-2000 plant canopy analyser (LI-COR, Lincoln, Nebraska, USA). Measurements were generally performed monthly from November until June of each season under diffuse radiation sky conditions towards sunset.

3.5 WATER POTENTIAL, GAS EXCHANGE AND WUE

3.5.1 Leaf and stem water potential

In 2018-2019 (fixed net trial), early morning leaf water potential (Ψ_{em}) was measured between 06:00 and 07:00 alternately between the 10 trees in the open and the 10 trees under the netting. One leaf per tree was measured using a Scholander pressure chamber (PMS Instrument Company, Albany, OR, USA). Measurements were performed once every month from December 2018 until June 2019.

In 2019-2020 at both the fixed net and draped net sites (KBV), and in 2020-2021 at the draped net site (EGVV), pre-dawn leaf water potential (Ψ_{pd}) was measured before 05:30 on ten trees per treatment. Two leaves per tree, one on each side of the row (east, west), were measured. Measurements were performed once every month from October 2019 until March 2020. The last measurements on 11 March 2020 were taken just after the 'Golden Delicious Reinders' harvest and six weeks before the 'Rosy Glow' harvest. Measurements could not be taken in April to June owing to the restrictions imposed by the COVID-19 pandemic. On the same measurement dates, the diurnal change in Ψ_{leaf} (unenclosed leaf) was measured using one leaf per tree. Measurements were performed from 06:00 until 15:00 in the pre-harvest period, and from 07:00 until 18:00 in the post-harvest period. Measurements were alternated between the treatments to reduce variance in data between the treatments owing to gradual changes in sun exposure and transpiration.

In 2019-2020 and 2020-2021, the midday stem water potential (Ψ_{stem}) was measured on the ten trees per treatment. Measurements were performed once per month from October until April (2018-2019) and from October until March (2019-2020; this was the last measurement date in 2020 owing to restrictions imposed as a result of the COVID-19 pandemic). We used the enclosed leaf method, with two mature leaves per tree, positioned close to the main stem at about 1.2 metres height. The leaves were enclosed at least one hour prior to measurement at mid-day between 12:00 and 14:00, using zip-lock, silver reflective stem water potential bags (PMS Instrument Company, Albany, OR, USA) to allow for equilibration between the leaf and stem xylem water potential.

3.5.2 Leaf gas exchange

The measured leaf gas exchange parameters included net CO_2 assimilation rate (A), stomatal conductance (g_s), and transpiration rate (E), obtained using a LI-6800 photosynthesis system (Li-Cor, Lincoln, NE, USA). In 2018-2019, the photosynthetic photon flux density (PPFD) provided by the red/blue LED lamp inside the cuvette was set at 1500 µmol m^{-2} s^{-1} for all measurements. Values thus represent light-saturated photosynthetic capacity. Photosynthetic light response curves were conducted on healthy leaves to assess the effect that a ca. 15% reduction in solar radiation under the net would have on A and g_s under a range of PPFD levels. Two sunlit leaves (one on each side of the tree) were measured on five trees per treatment in May and in June 2019. It was found that A began to decline at PPFD values below 900 µmol m^{-2} s^{-1} in both treatments, but detailed analysis remains to be done. In the next season (2019-2020, fixed and draped netting trials), the measurement protocol was changed. The PPFD in the leaf chamber was set to track the ambient PPFD experienced during the course of the morning in the open or under the net, thus simulating as far as possible the ambient conditions for each treatment. For the second draped netting trial in 2020-2021, the PPFD was set at 1500, 900 and 300 µmol m^{-2} s^{-1} for each leaf.

Other conditions inside the cuvette were ambient air temperature and relative humidity, and constant carbon dioxide (CO_2) concentration (400 µmol mol^{-1}) provided by an external CO_2 canister. A thermocouple inside the cuvette monitored leaf surface temperature (T_{leaf}). Leaf-to-air vapour pressure deficit (VPD_{leaf}) was calculated by the Li-Cor software. WUE_{inst} was calculated as the ratio of A to E.

In the first season, two leaves, one sunlit and one shaded, were measured at waist height from each side of every trial tree (10 trees per treatment) on a monthly basis from November 2018 until June 2019. Measurements were taken in the morning (08h30-12h30), alternating between the netted and open treatments. In the second season (fixed and draped netting trials), one sunlit leaf was measured at waist height from the eastern side of every trial tree on a monthly basis, from November 2019 until March 2020. Thereafter, COVID-19 restrictions prevented further measurements. In the third season (second draped netting trial), measurements were taken monthly from October 2020 to June 2021 on the ten trees per treatment.

3.6 TREE TRANSPIRATION AND ORCHARD FLOOR EVAPORATION

3.6.1 Tree transpiration using the heat ratio sap flow method

Sap flow methods are commonly used to measure the transpiration (T) of fruit trees (Green et al., 2003; Dzikiti et al., 2011; Gush and Taylor, 2014). Three most widely used methods are the heat ratio sap flow method (HRM) (Burgess et al., 2001), thermal dissipation probes (also called Granier probes or TDPs) (Granier, 1985), and the tissue heat balance method (Sakuratani, 1981). Each of these methods has its own advantages and disadvantages. For example, the HRM method is appropriate for woody plants with stem sizes larger than 40 mm in diameter. This technique is particularly suitable for operation at remote sites given that it does not require continuous heating and the measurements are automated. On the other hand, in the TDP and tissue heat balance methods, heat is applied continuously into the trees and running costs can easily escalate given the need for frequent battery changing. Both the TDP and HRM methods require that the temperature sensors be implanted into the sapwood. So the first step is often to determine the depth of the sapwood. The HRM method needs additional data on the moisture content of the sapwood, tissue wounding effects and wood density.

Advantages of sap flow methods are that; 1) they provide direct measurements of T, and 2) when combined with ET measurements, water use can be partitioned between the beneficial and non-beneficial uses. The main disadvantages of the sap flow techniques include substantial errors that can arise from wounding and density corrections in the case of the HRM method. Great care is therefore required when implementing these corrections. Accurate information is required on the sapwood area for both the HRM and TDP methods and these data are often obtained by destructive sampling or extracting cores with a stem corer. The latter method is suitable for high value trees such as fruit trees. Instrumented trees must be representative of the tree size distribution in the orchard. Scaling up from individual trees to orchard level transpiration can also introduce substantial errors and due care was absolutely critical to ensure representative information.

The improved heat ratio method (HRM) (Everson, unpublished) of the heat pulse velocity (HRM) sap flow technique was used to monitor the actual T of four trees per treatment (see layout in Figure 39). Each set of four trees in each treatment was served by one data logger installed inside a locked strong box in the middle of the netted or open row, within the tree row to facilitate tractor access. Installation at the draped nets site was performed from 25 to 27 September 2018. Trouble-shooting and problem-solving were completed by 26 October 2018. A few unforeseen equipment repairs were required which accounted for loss of data during the first few weeks of the first season.

The new system is still based on the HRM proposed by Burgess et al. (2001) and data were collected at hourly intervals throughout the growing season. However, set up of the hardware is somewhat different from what has been previously used in South African orchards. In the new system, each tree has a single tree box associated with it (Figure 39). Each tree box has eight short (1.75-2.0 m) T-type thermocouples, connected to the circuit board in pairs, in the sequence 1High/1Low, 2High/2Low, etc. The reference temperature for the thermocouples is measured by a precision thermistor located at the base of the circuit board. Unlike the old HRM system where the reference temperature was measured on the data logger panel, the current arrangement has the advantage that cable length does not limit the position of the tree box allowing trees that are far apart to be sampled. As in the old system, the thermocouple pairs were installed in the four cardinal directions around the stem at different depths in the sapwood to capture the circumferential and radial variations in sap velocity (Wullschleger and King, 2000).

Again, similar to the old system, a heater was placed in the middle of a pair of carefully drilled holes. One thermocouple hole (~2 mm diam.) was located upstream and the other downstream of the heater along the axis of the stem. Each thermocouple hole was precisely 0.50 cm from the central heater and the three holes were drilled using a drilling template to avoid probe misalignments. The system used short heaters (about 4 cm length) and these were also connected to the tree box. Unlike the old system in which the heat was applied through a relay control module, pulsing in the new system was done directly by the logger through a control port on the tree box. A small battery (7-12 Ah), housed in each tree box, supplied enough heat to the redesigned heaters that have to be enclosed in brass sleeves to improve thermal contact. Communication between the data logger and the electronics in the tree boxes was through a 22-core cable which could be as long as needed since the heat was applied close to the trees. The other end of the cable was connected to a multiplexer (Model: AM16/32B Campbell Scientific, Logan, UT, USA) which, in turn, was connected to the CR1000 data logger.

Figure 39 The improved heat pulse velocity sap flow system being used to monitor actual water use by the trees (transpiration, T) in the open and fixed shade netting trial. The insert shows an individual tree box.

At the Paardekloof draped nets site, the furthest tree was located about 25 m away from the data logger while the rest of the trees were within 15 m of the data logger (Figure 39). The advantages of this new system are that:

1. the monitored trees can be far apart allowing representative sampling of the orchard;
2. the equipment is not bulky and required small 7-12 Ah batteries;
3. the system was not prone to theft as there were no parts with a street value except for the small batteries, and;
4. the heat pulse velocity signals were quite smooth with fewer hits and misses (NaNs) compared to the old system meaning that less time was spent patching the data.

The disadvantage of the new system is that more, albeit smaller, batteries are required. For example, five batteries are required if four trees are instrumented. However, the system has low power requirements as the batteries can last more than a month if fully charged (>12.5 V). The new heaters are fairly thin and fragile and so they should be handled with care. Lastly, the bigger holes (> 2.2 m diam.) in which the brass sleeves are installed imply greater wounding of the tree, but this can be corrected for during data processing.

Table 2, Table 3 and Table 4 summarise the information on the stem sizes and the installation depths for the various probes at Paardekloof (fixed net site), Paardekloof (draped net site) and Southfield (draped net site), respectively. The sensors were installed on trees with different stem sizes to facilitate the scaling up of water use from the single trees to the orchard scale. Whole-tree T, in L d^{-1} for the instrumented trees in each treatment was derived as the sum of the sap flows in four concentric rings in the sapwood with flow in each ring calculated as the product of the sap velocity at each probe depth and the sapwood area represented by that probe. Orchard level transpiration for a given treatment (T, in mm d^{-1}) was calculated as the sum of the products of the sap flux density and the orchard sapwood area index (SAI) in each treatment for trees in different stem diameter classes such that:

$$T = \sum_{i=1,3} SAI_i \times U_i \tag{1}$$

where U_i is the sap flux density in each size class. Each of the instrumented trees was assigned an appropriate size class.

Differences in transpiration between the two treatments were compared as:

1. Orchard scale transpiration (T) differences based on equation 1;
2. Individual tree transpiration (T) expressed per unit leaf area. For this calculation, the total leaf area of the sap flow instrumented trees was estimated as accurately as possible.
3. Sap flux density, i.e. sap flow per unit sapwood area of the instrumented trees. The extent of the sapwood area was determined by injecting methylene blue dye into the trees at the end of the study.

Table 2 Stem size of the sap flow instrumented trees, and sap flow probe installation depths for the control and fixed nets treatments in Paardekloof ('Rosy Glow') during the 2019-2020 season.

Tree #	***Probe #***	***Treatment***				
		Open		***Shade netting***		***Insertion depths (mm)***
		Circum. (cm)	Diam. (cm)	Circum. (cm)	Diam. (cm)	
1	1					12
	2					20
	3	23.4	7.4	24.6	7.8	28
	4					35
2	5					12
	6	26.0	8.3	24.3	7.7	20
	7					28
	8					35
3	9					12
	10	25.0	8.0	26.0	8.3	20
	11					28
	12					35
4	13					12
	14	21.5	6.8	21.6	6.9	20
	15					28
	16					35

*Bark thickness ~ 0.6 cm

Table 3 Stem size of the sap flow instrumented trees, and sap flow probe installation depths for the control and draped nets treatments in Paardekloof ('Golden Delicious Reinders') during the 2019-2020 season.

Tree no.	Probe no.	Treatment				Insertion depths (mm)
		Open		Draped net		
		Circum. (cm)	**Diam. (cm)**	**Circum. (cm)**	**Diam. (cm)**	
1	1					12
	2					16
	3	29.48	9.39	21.79	6.94	20
	4					24
2	1					12
	2					16
	3	34.79	11.08	32.69	10.41	20
	4					24
3	1					12
	2					16
	3	29.99	9.55	32.50	10.35	20
	4					24
4	1					12
	2					16
	3	25.28	8.05	38.47	12.25	20
	4					24

Table 4 Stem size of the sap flow instrumented trees, and sap flow probe installation depths for the control and draped nets treatments in Southfield ('Golden Delicious') during the 2020/2021 growing season.

Tree #	Probe #	Treatment Open		Shade Netting		Insertion depths (mm)
		Circum. (cm)	Diam. (cm)	Circum. (cm)	Diam. (cm)	
1	1					12
	2					16
	3	37.8	12.03	54.4	17.32	20
	4					24
2	1					12
	2					16
	3	48.6	15.47	47.4	15.09	20
	4					24
3	1					12
	2					16
	3	53.4	17.00	49.5	15.76	20
	4					24
4	1					12
	2					16
	3	57.5	18.30	47.5	15.12	20
	4					24

3.6.2 Cover crop transpiration and soil evaporation

To understand how water use was partitioned into beneficial and non-beneficial uses (Figure 40) for open orchards and those under shade netting, data were collected on major sources of evaporation namely: tree transpiration (T), bare soil evaporation (E_s), and cover crop T. Tree transpiration was measured as described in section 3.6.1. E_s was monitored on selected days using micro-lysimeters at the beginning (spring), middle (summer) and end (autumn) of the growing season. The micro-lysimeters are made of 2 mm-thick PVC pipe, they were 100 mm deep and had an internal diameter of 85 mm. Each micro-lysimeter was equipped with one external cylinder made of 3 mm-thick PVC pipe which was 100 mm in diameter and 100 mm deep. Extraction of undisturbed cores from the top soil layer was conducted as described by Daamen et al. (1993) and the rate of E_s was calculated following the procedure explained by Li et al. (2010).

At least six micro-lysimeters were used at a time situated at different wet-dry locations on the orchard floor within each treatment. The data were collected at hourly intervals using a precision mass balance with a resolution of 0.01 grams. The total bare soil evaporation was calculated as the sum of evaporation from each lysimeter weighted with the area represented by each lysimeter on the orchard floor. New soil samples were loaded in the micro-lysimeters, e.g. after irrigation events or when measurements spanned over more than one day. Cover crop T was measured using miniature sap flow sensors (Model SGA2: Dynamax Inc., Houston, USA) that use the stem heat balance principle (Baker and van Bavel, 1987; Ntshidi et al., 2021). These sensors were installed during specific window periods when micro-lysimeter data were collected. The cover crop sap flow measurements were taken hourly from at least two plants (of the dominant species) with stem diameters in the range 1.5 to 3.0 mm. If SF_i is the sap flow (in $cm^3\ h^{-1}$) of a single cover crop plant whose leaf area was A_i, then the total cover crop transpiration (T_c, in mm) could be calculated as:

$$T_c = \sum_i \frac{SF_i}{A_i} \times LAI_c \qquad (2)$$

where LAI_c is the leaf area index (m^2 of leaf area per m^2 of ground area) of the cover crop estimated by measuring the leaf area in a 50 cm x 50 cm square grid (Figure 41) from at least four different positions in the work row of the orchard. The actual leaf area of the cover crop in the grid was measured using the leaf area meter (Model: Li-3000, Li-Cor, Nebraska, Lincoln, USA).

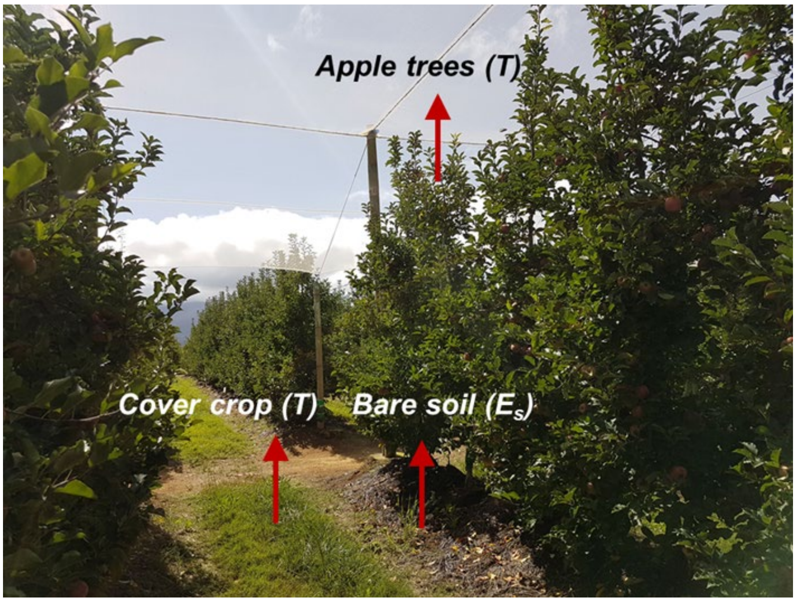


Figure 40 Different sources of evaporation in a high-density apple orchard.

Figure 41 Grid for sampling the leaf area index of the cover crops.

Records of when the cover crops were mowed were obtained from the farm. Transpiration by the cover crops outside the sap flow measurement period were subsequently estimated through a cover crop basal crop coefficient (K_{cbc}) calculated as:

$$K_{cbc} = \frac{T_c}{ET_o} \quad (3)$$

where ET_o is the reference evapotranspiration derived from the automatic weather station within each treatment. Similar sap flow and soil evaporation measurement methods were used at the two draped nets sites.

3.7 ORCHARD EVAPOTRANSPIRATION – SOIL WATER BALANCE

Orchard evapotranspiration was estimated using the soil water balance approach which required inputs of rainfall, irrigation and soil water content. Micrometeorological techniques that have been used in previous studies were deemed inappropriate for use in this study for the following reasons. Firstly, the presence of the shade nets disturbed the natural flow patterns of the wind over the orchard surfaces. This is a critical requirement for techniques such as the eddy covariance, surface renewal and scintillometry. Secondly, the small size of the orchards ensured that the fetch was not adequate for micrometeorological techniques. The presence of the nets over the orchards made the application of remote sensing based methods impractical. In the sections that follow, we provide details for the soil water balance which was the only viable technique to estimate orchard ET.

3.7.1 Calibration of soil water content sensors

Soil water content equipment were calibrated to check the accuracy of the CS650 and CS616 sensors in the soils. This was done by taking gravimetric soil samples for a range of soil water contents at selected depths to facilitate *in situ* calibration of the probes in each orchard. Statgraphics software (Statgraphics Technologies, Inc., The Plains, Virginia, USA) was used to obtain the mathematical relationships for the sensor calibration equations. Data points were considered as potential outliers if they deviated by more than two standard deviations from the model fitted and was only removed after careful inspection of the data. The sensors were calibrated for all the three study orchards used in this project.

3.7.2 Fixed netting trial (Paardekloof, KBV)

Orchard evapotranspiration (ET) was in previous research obtained by adding the crop ET calculated according to a soil water balance for the tree row, tractor row and cover crop areas. However, in the case of the ridged orchard tree rows several constraints prohibited use of this approach. Steep ridges (slopes of up to c. 30°) increased the potential for runoff and lateral movement of water in the soil profile from the ridge towards the tractor track and cover crop areas during and after irrigation, making assumptions for a one-dimensional soil water balance for the orchard areas located next to each other, invalid. Variation in irrigation system pressure furthermore resulted in uncertainties regarding the actual distribution of irrigation over the ridge, tractor track and cover crop areas.

A simple one-dimensional approach was therefore applied to the whole area allotted per tree and ET was calculated according to a soil water balance (Allen et al., 1998) on an hourly basis. It was assumed that runoff for the total area allotted per tree and capillary rise from the groundwater table was negligible. The field capacity (FC) or drained upper limit (DUL) values were determined from hourly soil water content graphs after rainfall or irrigation events for periods when tree water use was considered low. Hourly soil water content (m^3 m^{-3}) was weighed per soil sensor depth (200 mm, 600 mm, 1000 mm, 1300/1400 mm) over the three orchard areas (ridge, tractor track and cover crop) according to the soil volume allotted per sensor per area. Orchard profile soil water content was then calculated by multiplying the value per depth by the depth increment allotted, after which values were summed for the root zone (mm per 1.2 m or 1.4 m depth, depending on site specific root distribution). Irrigation volumes applied for one soil water balance replicate per treatment were obtained from the hourly electronic logging water meter.

For the second replicate, where irrigation volumes were monitored by a manual water meter, hourly irrigation volumes were estimated from logging water meter data in the adjacent irrigation line. This was achieved by using a statistical regression relationship established between volumes logged for the logging water meter and the manual water meter for comparable periods. The hourly irrigation amounts (mm) were calculated as (Volume applied/Full surface area). Rainfall was measured by a representative weather station. Deep percolation was estimated as the difference between orchard profile soil water content with irrigation and effective precipitation added and the field capacity value.

Precipitation was corrected for effectiveness according to Allen et al. (1998), taking the Penman-Monteith reference evapotranspiration (ET_o) into account. ET_o was derived from data provided by the standard weather station situated in the open. Hourly ET values were summed to obtain a daily ET value in mm. Where the hourly soil water balance resulted in unrealistic daily ET values (i.e.$1.4<(ET/ET_o)<0$) the daily ET was estimated from regression relationships obtained between daily ET and ET_o for each of the soil water balance sites. This enabled calculation of monthly averaged ET and total seasonal ET.

3.7.3 Draped netting trial (Paardekloof, KBV)

Orchard evapotranspiration for the 'Golden Delicious Reinders' draped netting orchard was calculated using the same approach as applied for the 'Rosy Glow' orchard below fixed netting (see section 3.7.2).

3.7.4 Draped netting trial (Southfield, EGVV)

In order to calculate the soil water balance the CS650/ CS616 soil water content measurements were converted to actual volumetric water content using the *in situ* calibration equations. The field capacity per CS650/ CS616 sensor was determined by inspection of hourly data after heavy rainfall during periods of minimal tree water use. The volumetric soil water content at specific installation depths were weighted to represent different depth increments to obtain the soil profile water content to 1.4 m depth. The sensors at 0.15, 0.45, 0.75, 1.05 and 1.3 m depths, respectively represent soil depth increments for 0 to 0.3, 0.3 to 0.6, 0.6 to 0.9, 0.9 to 1.2 and 1.2 to 1.4 m in the soil profile. The profile depth selected for ET calculation was based on root distribution observed during soil water balance equipment installation.

Evapotranspiration was calculated according to the universal soil water balance on a daily basis (Allen et al. 1998) using the soil water content logged at 0h00. The rainfall was measured by a representative weather station and was corrected for effectiveness according to Allen et al. (1998), taking the Penman-Monteith reference evapotranspiration (ET_o) into account. The irrigated amount (mm) was calculated as (Volume applied/Wetted area). A wetted radius of 3 m was used for the microsprinkler and the wetted widths for the tree row, tractor track and cover crop areas for the different soil water balance installations. The runoff and drainage components of the soil water balance were not measured. It was assumed that runoff would be negligible on the sandy soils irrigated according to best practice. Deep percolation was estimated as the difference between orchard profile soil water content with irrigation and effective rainfall added and the field capacity value. The ET was calculated separately for the tree row, tractor track and cover crop areas and the respective volumes were expressed as depth in millimetres over the full orchard surface area. Orchard ET was calculated by adding the ET of the different components.

The ET was calculated daily, but for 5 November 2020 until 3 May 2021 for periods between irrigations (day of irrigation until day before next irrigation). The ratio of actual ET to reference ET according to Allen et al. (1998) was calculated. A data set was selected which excluded data reflecting non steady-state conditions after heavy rainfall or irrigation (negative values, $ET:ET_o > 1.4$, excessive drainage). To obtain an estimate of seasonal ET the average of available $ET:ET_o$ data was taken for ten day intervals from the beginning of October 2020 until end June 2021. To obtain daily values ratios were interpolated from the middle of each ten-day period to the middle of the following ten day period. The exception was at the beginning and end of the season where the values for the first/ last five days remained similar to the ratio for the nearest ten-day period. Daily ET for most of the irrigated season and periods after heavy rainfall during which the soil water balance was not in equilibrium was estimated as $ET:ET_o$ ratios multiplied by ET_o (Allen et al., 1998).

3.7.5 Water saving

Water savings per hectare (m^3 ha^{-1}) and per ton of fruit produced (m^3 ton^{-1}) under the nets and in the open were provisionally calculated (for 'Rosy Glow' and 'Golden Delicious Reinders' in 2019-2020 and 'Golden Delicious in 2020-2021) using two approaches:

1. The difference calculated from ET data (representing potential savings); for this we used both ET data (to estimate water savings in m^3 ha^{-1}) and yield data provided by the farm (to estimate water savings in m^3 ton^{-1}).
2. The difference in irrigation applied in the open and netted treatments (representing real savings); for this we used data provided by the farm.

3.8 YIELD, FRUIT MATURITY AND FRUIT QUALITY

3.8.1 Fixed netting trial (Paardekloof, KBV)

3.8.1.1 Fruit growth

From the end of fruit thinning (9 November 2018) until 18 March 2019, the equatorial diameter of two tagged fruit per tree (one on each side of the tree) was measured. The measurements were performed once per month. A t-test was performed for each observation date separately. The variables were absolute fruit diameter, percentage change in fruit diameter (relative to the first measurement date), and daily relative fruit diameter growth rate (mm growth per day since the first measurement date).

3.8.1.2 Yield, fruit maturity and fruit quality

All fruit on each trial tree were harvested. In 2019, two picks were performed: on 17 April (most mature red apples on the outer canopy and lower half of the tree) and on 26 April (the remainder of the fruit on the tree). During each pick, the number of fruit per tree and the mass of fruit harvested off each tree were recorded in the orchard. Yield (in t ha^{-1}) and yield efficiency (in kg cm^{-2} trunk circumference area) were calculated from the harvest data and trunk circumferences. On each date, a sample of 20 apples per tree was collected at random and taken to the fruit laboratory at the Department of Horticultural Science at Stellenbosch University for the assessment of quality and maturity. The following parameters were measured:

- Fruit size, using electronic calipers around the equatorial diameter.
- Fruit mass, recorded for each fruit with a digital balance.
- Percentage foreground red colour and red colour intensity (as for Pink Lady®) and ground colour, using industry colour charts (Unifruco Research Services, Bellville).
- Sunburn incidence and severity, using the Schrader and McFerson system for blushed apples.
- Percentage starch conversion, estimated using the iodine test with the industry starch conversion chart (Unifruco Research Services, Bellville).
- Fruit firmness, determined on opposite equatorial cheeks by means of a penetrometer (Fruit texture Analyzer, Guss Instruments, Strand, South Africa) with an 11-mm plunger.
- A composite juice sample was prepared from 20 pooled fruit by cutting a slice on both sides of each fruit from both eastern and western sides of the row and blending the pieces in a liquidizer (AEG Electrolux, Type JE-107 no. 91100085/ PNC 950075206, P.R.C). The juice total soluble solids (TSS (%) were determined using a calibrated hand-held refractometer (TSS 0-32%, Model N1, Atago, Tokyo, Japan).

The remainder of the fruit harvested during each pick was placed in commercial bins and taken to the pack house. Standard quality control procedures were performed on samples from the bins from the open and netted areas. Data was also provided by the pack house for each orchard on grading of the apples into various classes and the main defects found.

In 2020, all fruit on the 10 trial trees per treatment were harvested on 21 April 2020 for the fixed nets experiment. It was planned to harvest in two picks on the basis of maturity and red colour, but this was thwarted by the strict travel restrictions imposed during the early part of the COVID-19 lockdown. We were able to obtain permits for the once-off harvest on 21 April. During the harvest, the mass of fruit harvested off each tree was recorded in the orchard (but not the number due to time limitations). Yield (in t ha^{-1}) and yield efficiency (in kg cm^{-2} trunk circumference area) were calculated from the harvest data and trunk circumferences. A sample of 20 apples per tree was collected at random and taken to the fruit laboratory at the Department of Horticultural Science at Stellenbosch University for the assessment of quality and maturity. The parameters listed above were measured, with the exception of peel red colour, which was accidentally omitted from the lab instruction list owing to the pressure experienced by the researchers and lab staff.

The remainder of the fruit harvested from the open and netted blocks was placed in commercial bins and taken to the pack house. Standard quality control procedures were performed on samples from the bins from the open and netted blocks. Data were also provided by the pack house for each block on the yield and mean fruit mass, and the main quality factors, namely; fruit size distribution, red colour, sunburn, hail damage and ground colour (green).

3.8.2 Draped netting trial (Paardekloof, KBV)

3.8.2.1 Fruit growth

From the end of fruit thinning (5 November 2019) until 6 February 2020, the equatorial diameter of two tagged fruit per tree (one on each side of the tree) was measured. The measurements were performed once per month. After 6 February, COVID-19 prevented further measurements. A t-test was performed for each observation date separately. The variables were absolute fruit diameter, percentage change in fruit diameter (relative to the first measurement date), and daily relative fruit diameter growth rate (mm growth per day since the first measurement date).

3.8.2.2 Yield, fruit maturity and fruit quality

All fruit on the 10 trial trees per treatment were harvested on 25 February 2020. To facilitate the harvest without removing the draped net and exposing the fruit to the full sunlight, the net was lifted up and fastened above the rows until the end of the trial harvest. During the harvest, the number of fruit and the mass of fruit harvested off each tree were recorded in the orchard. Yield (in t ha^{-1}) and yield efficiency (in kg cm^{-2} trunk circumference area) were calculated from the harvest data and trunk circumferences. A sample of 20 apples per tree was collected at random and taken to the fruit laboratory at the Department of Horticultural Science at Stellenbosch University for the assessment of quality and maturity using the methods described in Deliverable 3. The same parameters as listed in section 3.8.2.1 were assessed, with the exception of red peel colour, and the addition of retiform and stem-end russet.

The remainder of the fruit harvested from the open and netted rows was placed in commercial bins and taken to the pack house. Standard quality control procedures were performed on samples from the bins from the open and netted rows. Data was also provided by the pack house for each treatment on the yield and mean fruit mass, and the main quality factors, namely; fruit size distribution, sunburn, hail damage and ground colour (green).

3.8.3 Draped netting trial (Southfield, EGVV)

3.8.3.1 Fruit growth

At the draped nets site in Southfield, fruit growth was monitored only in the crop load trial. On 9 December 2020, one day after fruit hand thinning, three representative fruit per replicate were tagged, on the outer canopy, at approximately shoulder height. Two fruit were tagged on the east side and one on the west side of the row. Fruit equatorial diameter was recorded monthly from 9 December 2020 until 22 February 2021. A two-way ANOVA was performed for each observation date separately. The variables were absolute fruit diameter, percentage change in fruit diameter (relative to the first measurement date), and daily relative fruit diameter growth rate (mm growth per day since the first measurement date).

3.8.3.2 Yield, fruit maturity and fruit quality

On 4 March 2021, a sample of 20 fruit per tree was harvested at random, at around shoulder height, from the east and west side of the row, from all the experimental trees (main trial and crop load trial; we present results only for the main trial). For this sampling, the draped net was not removed but only partially lifted to facilitate the removal of the fruit (Figure 42). The trees thereafter remained fully enclosed until final harvest. The samples were taken to the fruit laboratory at the

Department of Horticultural Science at Stellenbosch University for the assessment of quality and maturity, as described in section 3.8.2.2.

The final full harvest occurred from 8-10 March 2021. The draped net was removed tree by tree to ensure that fruit on trees not yet harvested would not receive sunburn damage as a result of sudden exposure to full sunlight. The total mass of the fruit per tree was recorded using a portable electronic scale and converted to yield (t ha^{-1}). The number of fruit per tree was not recorded due to limited picker availability and time constraints. This variable was estimated using the total fruit mass per tree and the average individual fruit mass determined from the laboratory sample. The harvested fruit were placed into commercial bins and taken to the pack house. However, we were unable to obtain pack house data for quality control and pack outs.

Figure 42 Draped net over 'Golden Delicious' crop load trial trees being removed on a tree by tree basis during the harvest.

3.9 WATER PRODUCTIVITY

3.9.1 Fixed netting trial (Paardekloof, KBV)

3.9.1.1 Seasonal transpiration and evapotranspiration

From the daily sap flow data, the transpiration was modelled as L $tree^{-1}$ day^{-1} and as mm day^{-1}, as described in section 3.6.1 of this report. The total seasonal transpiration was then summed for the period 09/11/2018 to 19/05/2019 (first season) and 28/09/2019 until 05/06/2020 (second season). In 2018-2019 we only started to gather reliable sap flow data one month into the season, so the values of water use prior to 09/11/2018 are not included in the seasonal totals, which results in a slight underestimation of the water use, and a possible overestimation of the WP.

In 2019-2020, a small amount of transpiration was likely a few days prior to 28/09/2019, and between 06/06/2020 and leaf drop in June 2020, for which we do not have sap flow data. However, our under-estimate for total seasonal transpiration is likely to be very small, so that for calculation purposes we make the assumption that transpiration was zero from 01/07/2019 until 27/09/2019 and after 06/06/2020. For the second season, daily evapotranspiration was calculated as described in section 3.7.2 of this report. We used the calculation of total ET for 01/07/2019 until 30/06/2020 (full year).

3.9.1.2 Yield, pack out and gross income

The methods used are presented in section 3.8.1 of this report. The pack house supplied the data on orchard yield and grading of the fruit into four classes, for the full open (control) area and the full netted area.

The classes used were:

- Class 1 Pink Lady® which meets the high quality standards to be sold under the trade mark name, and fetches a premium price;
- Class 1 'Cripps Pink' which meets the quality standards to be sold as this cultivar but fetches a lower price compared to Pink Lady®;
- Super which fetches an intermediate price (only 2018-2019);
- Class 3 which does not meet the requirements for the first three classes and fetches the lowest price.

Gross orchard income (Rand) per hectare and per ton of fruit was provided by the farm. This was calculated using farm data for yield, the percentage of fruit graded into each of the four classes in the pack house, and the market price obtained for each class. It should be noted that packing and marketing were conducted in several batches and the pack house and farm data are more complex; therefore, average prices were employed. Our income values are therefore not exactly the same as the values shown in farm financial statements, but these were not made available.

The unique challenges of the 2020 marketing season (COVID-19) led to a situation where actual prices achieved do not reflect the actual fruit quality and price potential (in a normal year). For this reason, a pooled price per class was supplied by the pack house, for use in the calculations of WP_e, together with the quality-based packout data. From this data, gross orchard income (Rand) per hectare and per ton of fruit were calculated. We emphasise that packing and marketing were conducted in response to the complex COVID-19 situation. Our income values are therefore not exactly the same as the values shown in farm financial statements, which are not made available.

3.9.1.3 Physical and economic water productivity

First, we calculated the WP_p of the orchard as kg of fruit produced per m^3 of water transpired during the season (as measured through sap flow monitoring). The calculation was based on the yield (t ha^{-1}) of the whole orchard and the seasonal transpiration (m^3 ha^{-1}) calculated as the average of four representative monitored trees.

*WP_p (kg/m^3) = (Yield*1000) / Seasonal transpiration* (4)

Second, we also present the water use per ton of production (WUT) as m^3 ton^{-1} (equivalent to L kg^{-1}) since this value is also sometimes presented in the literature (going under various terms such as “water footprint”).

WUT (m^3 ton^{-1}) = Seasonal transpiration / Yield (5)

Third, we calculated the WP_e as the gross income of the harvest (Rand ha^{-1}) per m^3 of water transpired per ha (as measured through sap flow monitoring). This factors in the overall quality and marketability of the fruit. Again, the calculations were based on the yield of the sap flow monitored trees per treatment, and the total orchard yield.

WP_e (R/m^3) = Orchard gross income / Seasonal transpiration (6)

For the 2019-2020 season only, we performed the same set of calculations but using the seasonal evapotranspiration (ET) in place of seasonal transpiration.

3.9.2 Draped netting trial (Paardekloof, KBV)

3.9.2.1 Seasonal transpiration and evapotranspiration

The calculation of daily and seasonal transpiration for the period 05/10/2019 until 11/06/2020 was presented in section 3.6.1. Some small additional transpiration was likely prior to 05/10/2019, so that our seasonal total is likely very slightly under-estimated. We are confident that transpiration was close to zero after 11/06/2020 since all the leaves had fallen by that date. Daily evapotranspiration was calculated as described in section 3.7.3 of this report and we use the calculation of total ET for 14/09/2019 until 30/06/2020.

3.9.2.2 Yield, packout and gross income

The methods used are presented in section 3.8.2. Data on yield and pack out (grading into classes) and price per class was provided by the farm and pack house.

The classes used (for ‘Golden Delicious Reinders’) were:

- Class 1 – which meets the high quality standards for the export market, and fetches a premium price;
- Class 2 – which meets the quality standards for the local market but fetches a lower price;
- Class 3 – which does not meet the requirements for the first two classes and fetches the lowest price.

Please refer to section 3.9.1.2 for further information on the challenges experienced in the 2020 marketing season.

3.9.2.3 Physical and economic water productivity

We used the same methods as described in section 3.9.1.3.

3.9.3 Draped netting trial (Southfield, EGVV)

3.9.3.1 Seasonal transpiration and evapotranspiration

The calculation of daily and seasonal transpiration for the period 05/10/2019 until 11/06/2020 was presented in section 3.6.1. Some small additional transpiration was likely prior to 05/10/2019, so that our seasonal total is likely very slightly under-estimated. We are confident that transpiration was close to zero after 11/06/2020 since all the leaves had fallen by that date. Daily evapotranspiration was calculated as described in section 3.7.4 of this report and we use the calculation of total ET for 14/09/2019 until 30/06/2020.

3.9.3.2 Yield, packout and gross income

The methods used are presented in section 3.8.3. Since we could not obtain data on yield, pack out (grading into classes) and price per class from the farm and pack house, we estimated the pack out from our laboratory assessment of fruit quality and size distribution, and used a set of theoretical prices per class.

The classes used (for 'Golden Delicious') were:

- Class 1 – which meets the high quality standards for the export market, and fetches a premium price;
- Class 2 – which meets the quality standards for the local market but fetches a lower price;
- Class 3 – which does not meet the requirements for the first two classes and fetches the lowest price.

3.9.3.3 Physical and economic water productivity

In this season, the calculation of WP was based on the seasonal transpiration (m^3 ha^{-1}) and yield (t ha^{-1}) of the ten sap flow monitored trees per treatment. The calculations for WP were as shown in section 3.9.1.3. We also performed the same set of calculations but using the seasonal evapotranspiration (ET) in place of seasonal transpiration.

3.10 MODELLING WATER USE OF OPEN AND NETTED ORCHARDS

3.10.1 Evapotranspiration model description

In this project we applied a version of the Shuttleworth and Wallace model that was developed by Dzikiti et al. (2017 and 2018a) as part of the previous WRC/Hortgro apple project. Since modelling the microclimate change under the nets is quite complex, we used the measured weather data both for the open and netted treatments. However, for practical irrigation management under nets, it is desirable to develop a water use model that uses only the readily available weather data from a standard weather station as inputs as growers are unlikely to install separate weather stations under nets. In this section we briefly describe the evapotranspiration model that was previously applied to apple orchards in South Africa (Dzikiti et al., 2018 a, b). We validate the model as developed with the independent data collected in this study.

Given the heterogeneous nature of orchards comprising trees in rows and wide-open spaces between the rows, the Shuttleworth and Wallace (1985) model has previously been applied to orchards (Ortega-Farias et al., 2012; Ortega-Farias and López, 2012). According to this model, evapotranspiration (ET, in W m^{-2}) is calculated as the algebraic sum of transpiration from the trees (T, in W m^{-2}) and evaporation from the orchard floor, hereafter called substrate evaporation (E_s, in W m^{-2}) such that:

$$ET = T + E_s \qquad (7)$$

where

$$T = C_c \frac{\Delta A + \left\{ \dfrac{\rho c_p D - \Delta r_a^{\ c} A_s}{r_a^{\ a} + r_a^{\ c}} \right\}}{\Delta + \gamma \left\{ 1 + r_s^{\ c} / (r_a^{\ a} + r_a^{\ c}) \right\}} \tag{8}$$

$$E_s = C_s \frac{\Delta A + \dfrac{\left\{ \rho c_p D - \Delta r_a^{\ s} (A - A_s) \right\}}{r_a^{\ a} + r_a^{\ s}}}{\Delta + \gamma \left\{ 1 + r_s^{\ s} / (r_a^{\ a} + r_a^{\ c}) \right\}} \tag{9}$$

where C_c is a dimensionless canopy resistance coefficient; C_s is the substrate resistance coefficient, also dimensionless; Δ is the slope if the saturation vapour pressure-temperature curve (kPa K^{-1}), c_p is the specific heat at constant pressure (J kg^{-1} K^{-1}), ρ is the density of air (kg m^{-3}); D is the vapour pressure deficit of the air at the reference height (kPa), r_a^a (in s m^{-1}) is the aerodynamic resistance between canopy source height and reference level, r_a^c (in s m^{-1}) is the boundary layer resistance of the canopy, r_s^c (s m^{-1}) is the canopy resistance, r_s^s (s m^{-1}) is the surface resistance of the substrate, r_a^s (s m^{-1}) is the aerodynamic resistance between the substrate and the canopy source height and γ is the psychrometric constant (kPa K^{-1}). A is the available energy (W m^{-2}) absorbed by the orchard calculated as the difference between the net radiation and the soil heat flux, and A_s (W m^{-2}) is the available energy at the orchard floor calculated from A using Beer's law.

The original Shuttleworth and Wallace (1985) used a constant stomatal resistance (r_{sT}) of 400 s m^{-1}, while the soil surface resistances (r^s_s) were fixed at 0, 500, and 2000 s m^{-1} for wet, moderately wet, and dry soils, respectively. The improved apples model used a variable stomatal conductance ($g_{sT}=1/r_{ST}$) following Jarvis (1976). According to this method, if $g_{s\max}$ is the maximum stomatal conductance for apples, then the stomatal conductance at any given time is moderated by environmental stress factors according to:

$$g_{ST} = g_{s\max} \times f(R) \times f(T) \times f(VPD) \times f(\theta) \quad (\text{m s}^{-1}) \tag{10}$$

where *f(R), f(T), f(VPD)* and *f(θ)* are the solar radiation (*R*), air temperature (*T*), vapour pressure deficit of the air (*VPD*) and soil water content (*θ*) stress factors with values between 0 and 1. The stress factor expressions took the following forms:

$$f(R) = \frac{R}{R + k_r} \tag{11}$$

$$f(T) = \left(\frac{T - T_{\min}}{T_{opt} - T_{\min}} \right) \times \left(\frac{T_{\max} - T}{T_{\max} - T_{opt}} \right)^{\left((T_{\max} - T_{opt}) / (T_{opt} - T) \right)} \tag{12}$$

$$f(VPD) = e^{-k_{vpd} * VPD} \tag{13}$$

$$f(\theta)=\begin{cases}1 & \theta\geq\theta_{FC}\\ \left(\dfrac{\theta-\theta_{WP}}{\theta_{FC}-\theta_{WP}}\right)^{\beta} & \theta_{WP}<\theta<\theta_{FC}\\ 0 & \theta\leq\theta_{WP}\end{cases} \quad (14)$$

where k_r, k_{vpd}, and β are parameters obtained by model optimization. Equation 11 has been applied on maple trees (*Acer rubrum*) by Bauerle et al. (2002), while equations 12 and 13 were used in a sugarcane ET model in South Africa by Bastidas-Obando et al. (2017). Equation 14 was adopted from Egea et al. (2011) where θ_{FC} and θ_{WP} represent the volumetric soil water content at field capacity and permanent wilting point, respectively in the root zone. The LAI was measured using a leaf area meter (Model: LI 2000, LI-COR Inc., Nebraska, USA) under diffuse radiation sky conditions, either before sunrise or at sunset. A detailed description of the model parameterization is given in Dzikiti et al. (2018a).

The soil surface resistance was derived from the soil water content in the top 15 cm (θ_{15}) by fitting a power function proposed for pine forests by Poyatos et al. (2007) as:

$$r^{s}{}_{s}=\begin{cases}0 & \theta\geq\theta_{FC}\\ b_1\left(\dfrac{\theta_{15}}{\theta_{15FC}}\right)^{b_2} & \theta_{WP}<\theta<\theta_{FC}\\ 2000 & \theta<\theta_{WP}\end{cases} \quad (\text{s m}^{-1}) \quad (15)$$

b_1 and b_2 are model parameters obtained by calibrating the soil evaporation sub-model soil evaporation data measured using micro-lysimeters. The symbol θ_{15} represents the hourly average soil water content at the 15 cm depth, and θ_{15FC} is the volumetric water content at field capacity at the 15 cm depth. The model was developed using the ModelMaker software package (Cherwell Scientific, UK).

3.10.2 Statistical analysis

Statistical differences between the measured and modelled transpiration rates were determined using the Student t-test (α = 0.05). The performance of the modified Shuttleworth and Wallace model was evaluated based on the root mean square error (RMSE), and the mean absolute error (MAE). The predictive accuracy of the model was established using the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) computed as:

$$NSE=1-\left[\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs}-Y^{mean})^2}\right] \quad (16)$$

where Y_i^{obs} is the i^{th} observation of the daily ET, Y_i^{sim} is the i^{th} simulated ET, and Y^{mean} is the mean ET value and n is the total number of observations. The NSE ranges between $-\infty$ and 1.0 with NSE = 1.0 being the optimal value and values between 0 and 1.0 are generally viewed as acceptable levels of performance (Moriasi et al., 2007). Values ≤0.0 indicate that the mean observed value is a better predictor than the simulated value which indicates unacceptable model performance.

3.10.3 Input data

The model is run at hourly time steps and takes readily available climate data as inputs namely the solar radiation, average air temperature, relative humidity, and wind speed. Orchard information to be input into the model include the average tree height and the orchard leaf area index (LAI) and the average volumetric soil water content in the rootzone. The site altitude above sea level is also required. The hourly simulations, done in equivalent energy units (i.e. W m^{-2}), are subsequently converted to equivalent depth units (i.e. mm d^{-1}) in Excel.

In this study there were challenges with the input data mainly due to power losses at the weather stations. There was a huge delay in the sap flow data, used to derive the transpiration due to equipment malfunctioning. We were unfortunate to receive a bad batch of thermocouples and it took us a while to diagnose the source of the bad data. Replacement sensors had to be shipped from KwaZulu-Natal after a few weeks. The following criteria were used to select the data that was used:

1) Only days with good quality data were selected;
2) Days with complete 24 hours data were used;
3) Data for days with both sap flow and weather data were used.

Based on this criteria there were 77 days of data for the control treatment and 63 days for under the fixed nets.

3.10.4 Crop coefficients

Single crop coefficients were calculated for days on which the soil water balance was in equilibrium, and a regression relationship was established between ten-day averages of K_c and day of season starting 1 September. Daily K_c values were estimated for days on which the soil water balance was not in equilibrium and the ET was estimated for those days using the soil water balance equation and the daily ET_o. The total monthly and seasonal ET were therefore calculated using daily soil water balance based ET and modelled ET derived from these crop coefficients (K_c) and ET_o.

The single crop coefficients for the control and net treatments were determined according to the guidelines of FAO56 (Allen et al., 1998):

$$Kc = ET / ET_o \tag{17}$$

Where, Kc is crop coefficient [dimensionless], ET is crop evapotranspiration [mm d-^{1}] and ET_o is reference crop evapotranspiration [mm d^{-1}] calculated using ARC AWS data. The reference surface is a hypothetical grass reference crop (Allen et al., 1998). The ET values were obtained from the daily soil water balance.

The basal crop coefficient (K_{cb}), which represents primarily the transpiration component of ET (Allen et al., 1998) was calculated as:

$$Kcb = T / ET_o \tag{18}$$

Where, T is the orchard transpiration (in mm d^{-1}) derived from the sap flow measurements.

3.11 BUDGETING LIFETIME COSTS AND INCOME OF OPEN AND NETTED ORCHARDS

The question to be answered in this part of the study is whether, and to what degree, the savings associated with changed water use under netting compared to the open can help to make a stronger financial case for the benefits of installing netting over apple orchards. The installation of fixed or draped netting is highly capital-intensive and this investment must be returned over time through a beneficial combination of orchard level costs and income – thus profitability. This can arise through one or more of the following responses under netting: increased yield, improved fruit quality and packout, higher average price and gross income for the crop, changes in input costs for plant protection, nutrition and plant growth regulators, changes in labour costs, and (of particular interest for this project) changes in water use and electricity for pumping water. In our model we aimed to identify and incorporate the key costs and changes in income that are altered when netting is used, based on quantitative data from our field measurements as well as data provided by the farm. Since enterprise modelling is in essence a simulation over the orchard lifetime, it also offers the opportunity to run the model using different sets of assumptions (scenarios) to gain a better understanding of the relative importance of key elements and key risks over the orchard lifetime, with respect to annual and cumulative profits.

3.11.1 The enterprise model

The Dutoit Agri of farms (including Paardekloof, where this study was conducted) have developed an enterprise model for their own planning purposes that is well suited to our research purposes since it already incorporates scenarios for the use (or not) of fixed and draped netting, and is already parameterised for orchard level costs and income based on real data over many years. They kindly made this model available and we have adapated it for our research purposes. There is an agreement with Dutoit Agri that actual costs and income and resulting graphs as used for their planning purposes will not be made public. In this section we present a new set of graphs arising from the set of scenarios described in sections 3.11.4 and 3.11.5.

3.11.2 Model structure

The model is a multi-year apple orchard budget model set up for 25 years. This allows for the simulation of financial benefits of using shade netting that may only arise over a longer period, and ultimately over the orchard lifetime. The model makes use of Microsoft Excel and covers inputs, calculations and outputs (graphs and values). Although the model can be run for actual orchard size in hectares, we have standardised our model runs on one hectare. The baseline model is set up to start in 2020 (orchard establishment), i.e. for planning purposes. Our scenarios make use of this approach in a more theoretical manner, but in other scenarios we adjust the model to start in the actual year of establishment of this orchard (2010) with the fixed netting installed end-2014. The main spreadsheet covers capital investment (both orchard establishment and the additional cost of netting if used), annual production costs and annual profit. Sub-models are used to calculate orchard establishment costs, annual production costs, and farm gate prices obtained per class of fruit.

3.11.2.1 Orchard establishment costs

For 'Rosy Glow', this sub-model is set up for planting density of 3.5 x 1.25 m (the density of the 'Rosy Glow' orchard used in this study; thus 2285 trees/ha). For 'Golden Delicious Reinders', the sub-model was set up for a planting density of 4.0 x 1.75 m, giving 1428 trees/ha. The parameters include removal of previous trees, labour, fertilisation, soil preparation, soil fumigation, drainage, cover crop, irrigation system, nursery trees and royalties per tree (as is the case for 'Rosy Glow'), support structure and trellising (differentially costed for net or no net) and netting. The costs increase annually by 5%. For some scenarios we start this sub-model in 2020, and for others we simulate the actual history by starting in 2010. This is achieved theoretically (rather than with actual data for this orchard) using 5% inflation so that the value in year 2020 is the same as for the approach starting in 2020. We did this separately for netted and open orchards. The values generated in this sub-model are fed into the main model spreadsheet.

3.11.2.2 Annual production costs

This sub-model in its original form used a standard annual production cost per hectare for an apple orchard in 2020, multiplied by a cultivar-specific factor. An inflation rate of 5% is used. Again, we ran this model from 2020 for some scenarios, and for others we ran it from 2010 using 5% inflation. The same sub-model was used for the netted and open scenario. This is explained by the following calculations:

From the data collected in this orchard over two seasons (our primary source of information), supplemented with information from the published literature as well as a similar study performed for the citrus industry in South Africa (Brown, 2018), we identified the following list of costs that could be expected to differ between open and netted orchards (Table 5):

Table 5 Theoretical and actual differences in variable production costs under netting and in the open for apple orchards.

Cost item	Cost change under net compared to open (likely based on available information)	Cost change under net in netted orchard compared to open
Water	Decreases	0%
Electricity for pumping	Decreases	-10%
Fertiliser	Variable	0%
Rest breaking and fruit thinning chemicals	Variable	0%
Growth regulator (Regalis)	Increases	0%
Beehives (pollination services)	Increases	0%
Labour (pruning)	Increases	0%
Labour (net maintenance)	Only for netted orchards	+R1600/ha

The Dutoit Agri enterprise model does not specifically account for the cost of water. The farm sources its water from its own farm dams (the study orchards are given dam water) and groundwater. Thus there are no water costs associated with a water scheme. Water costs are only linked to water licences that are dealt with separately from farm operating budgets.

To estimate the reduction in electricity costs for pumping, the annual farm electricity bill was multiplied by a factor of 0.7 to estimate irrigation-related electricity use, and then divided by the total hectares to estimate cost per hectare. Based on the results presented in this report, we assumed a 10% reduction in irrigation pumping under the net compared to the open.

For the trial orchards, the overall costs were estimated at less than R500/ha higher under the net compared to the open. We regard this as a negligibly small difference and do not factor this sub-analysis into the model runs. However, the sub-model can be adjusted for the other orchards to account for possible differences between the net and open areas in these variable costs, including water.

3.11.2.3 Prices

This sub-model was added to the original Dutoit Agri model to allow us to estimate prices per class of fruit for either a 2020 or a 2010 starting date. The 2020 values are theoretical values for four classes of fruit supplied by Dutoit Agri (Classes 1, 2, 3 and fruit not sent for packing), for 'Rosy Glow' or 'Golden Delicious Reinders'. We used 3% inflation in prices for both starting years.

3.11.2.4 Main model spreadsheet

Separate spreadsheets were used for open and netted orchards. The model included:

1. Orchard establishment + netting in either Year 1 (planned orchards) or Year 4 (this 'Rosy Glow' study orchard), depending on the scenario; in some scenarios the cost of replacing the net once over the orchard lifetime was added;
2. Annual production cost (inflation-adjusted) multiplied by a factor that ramps costs up over the first 6 years to 100% in Year 6 and thereafter;
3. Inflation-adjusted income, based on yield (ramped up to 100% in Year 8 – full-bearing), packout, and price per class of fruit. In open orchards, packout from Year 5 onwards is expected to be 50% Class 1, 40% Class 2, 10% Class 3, and 10% BU (juice, not sent for packing). For netted orchards it is expected to be 65% (Class 1), 25% Class 2, 10% Class 3 and 10% BU. For the scenarios simulating the actual history of this 'Rosy Glow' orchard these packout values were substituted with real values until 2020. Thereafter they were simulated. Similarly, yield data was also substituted with real data.

3.11.3 Model parameterisation

The original model was parameterised for a theoretical orchard planted in 2020, using Dutoit Agri data reflecting their average costs and income for 'Rosy Glow' or 'Golden Delicious Reinders'. We have kept the inputs for the establishment costs, the production costs and prices. However, we have substituted inputs for yield and packout as described in the scenarios (3.11.4, 3.11.5), and adjusted the starting values depending on the starting date (2010 or 2020).

3.11.4 Fixed net trial scenarios

We were unable to calculate the water savings in the first season (2018-2019) owing to problems with raw data required for the calculation of ET and seasonal irrigation.

We used a range of scenarios to analyse the overall costs and benefits of using netting over apple orchards compared to no net (Table 6). Each set of scenarios (e.g. Scenarios 1 and 2) is split into one assuming no net replacement and one assuming one net replacement after 15 years. The first six scenarios (1A to 4) model the ‘Rosy Glow’ orchard used for this study, with actual data inputs as made available by the farm or measured between 2018 and 2020, and assumptions based on the recent historical data thereafter. For Scenarios 1A, 2A, 3 and 4 we assumed a future yield of 110 t/ha (average for this orchard over the last three years), but tested a more moderate yield of 90 t/ha in Scenarios 1B and 2B. Scenarios 1 and 2 use a more optimistic estimate of future packout under the net, whereas Scenarios 3 and 4 use a more pessimistic estimate of future packout that is closer to the actual data for the last three years.

Scenarios 5-8 (Table 6) model a theoretical ‘Rosy Glow’ orchard planted at Paardekloof in 2020, either with or without fixed net (which, again, is either replaced or not replaced). The inputs for yield and packout are estimates based on the potential of such an orchard. A full-bearing yield of 90 t/ha is used, but the packout estimates are the more optimistic ones. In Scenarios 7 and 8 we add one (Scenario 7A and 8A) or two (Scenarios 7B and 8B) hail or sunburn events, resulting in decreased fruit quality and thus income in that year for the open orchard: OR = 80%; Class 1 = 30%; Class 2 = 50%; Class 3 = 20%.

Table 6 Description of the scenarios used to run the orchard level financial model comparing the use of nets versus no nets in 'Rosy Glow' apple orchards.

	Period	Net installed	Net replaced	Hail/ Sunburn event	Yield	Quality: OR	Quality: Class 1	Quality: Class 2	Quality: Class 3
Scenario 1A	2010-2034	2014	No	As occurred until 2020, reflected in packout	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 110t/ha	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 90%	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 50% (open) and 65% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 40% (open) and 25% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 10% (open) and 10% (net)
Scenario 2A	2010-2034	2014	Yes (2024)	As occurred until 2020, reflected in packout	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 110t/ha	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 90%	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 50% (open) and 65% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 40% (open) and 25% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 10% (open) and 10% (net)
Scenario 1B	2010-2034	2014	No	As occurred until 2020, reflected in packout	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 90t/ha	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 90%	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 50% (open) and 65% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 40% (open) and 25% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 10% (open) and 10% (net)
Scenario 2B	2010-2034	2014	Yes (2024)	As occurred until 2020, reflected in packout	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 90t/ha	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 90%	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 50% (open) and 65% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 40% (open) and 25% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 10% (open) and 10% (net)
Scenario 3	2010-2034	2014	No	As occurred until 2020, reflected in packout	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 110t/ha	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 90%	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 50% (open) and 55% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 35% (open) and 35% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 15% (open) and 10% (net)
Scenario 4	2010-2034	2014	Yes (2024)	As occurred until 2020, reflected in packout	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 110t/ha	Estimated for 2010-2014; Actual data from 2015-2020; thereafter 90%	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 50% (open) and 55% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 35% (open) and 35% (net)	Estimated for 2010-2016; Actual data from 2017-2020; thereafter 15% (open) and 10% (net)

Scenario 5	2020-2044	2020	No	None (factored into pack out)	Theoretical; full-bearing in Year 8 at 90t/ha	90% from Year 5 onwards	50% (open) and 65% (net) from Year 5 onwards	40% (open) and 25% (net) from Year 5 onwards	10% (open) and 10% (net) from Year 5 onwards
Scenario 6	2020-2044	2020	Yes (2034)	None (factored into pack out)	Theoretical; full-bearing in Year 8 at 90t/ha	90% from Year 5 onwards	50% (open) and 65% (net) from Year 5 onwards	40% (open) and 25% (net) from Year 5 onwards	10% (open) and 10% (net) from Year 5 onwards
Scenario 7A	2020-2044	2020	No	Event in 2027 (Year 8)	Theoretical; full-bearing in Year 8 at 90t/ha	90% from Year 5 onwards	50% (open) and 65% (net) from Year 5 onwards	40% (open) and 25% (net) from Year 5 onwards	10% (open) and 10% (net) from Year 5 onwards
Scenario 8A	2020-2044	2020	Yes (2034)	Event in 2027 (Year 8)	Theoretical; full-bearing in Year 8 at 90t/ha	90% from Year 5 onwards	50% (open) and 65% (net) from Year 5 onwards	40% (open) and 25% (net) from Year 5 onwards	10% (open) and 10% (net) from Year 5 onwards
Scenario 7B	2020-2044	2020	No	Events in 2027 (Year 8) and 2035 (Year 16)	Theoretical; full-bearing in Year 8 at 90t/ha	90% from Year 5 onwards	50% (open) and 65% (net) from Year 5 onwards	40% (open) and 25% (net) from Year 5 onwards	10% (open) and 10% (net) from Year 5 onwards
Scenario 8B	2020-2044	2020	Yes (2034)	Events in 2027 (Year 8) and 2035 (Year 16)	Theoretical; full-bearing in Year 8 at 90t/ha	90% from Year 5 onwards	50% (open) and 65% (net) from Year 5 onwards	40% (open) and 25% (net) from Year 5 onwards	10% (open) and 10% (net) from Year 5 onwards

3.11.5 Draped net trial scenarios

The scenarios used for 'Golden Delicious Reinders' (2019-2020, Paardekloof, KBV) were slightly adjusted as follows:

- For planned (future) orchards, draped net was added as a cost in Year 3, and for the real orchard and trial in 2019-2020 at Paardekloof it was added in Year 10; the assumption for both is that the net is re-used annually thereafter until it is replaced;
- No net replacement was added to each set of real orchard scenarios (cost of nets included only in 2019);
- Each set of planned orchard (future) scenarios assumed one net replacement (Year 17, 2036) except scenario 5 which assumed two net replacements (Years 11 and 19);
- Yield and packout input values were adjusted to reflect the expectations for such an orchard, or the actual yield history of the real orchard until 2020.

The first three scenarios model the ‘Golden Delicious Reinders’ orchard used for this study, with actual data inputs as made available by the farm or measured by the researchers in 2019-2020, and assumptions based on the recent historical data thereafter (Table 7). For scenarios 1 and 3 we assumed a future yield of 120 t/ha, but tested a more moderate yield of 100 t/ha in scenario 2. Scenarios 1 and 2 used a more optimistic estimate of future packout, whereas scenario 3 used a more pessimistic estimate of future packout.

Scenarios 4-7 (Table 7) represent a theoretical ‘Golden Delicious Reinders’ orchard planted at Paardekloof in 2020, either with or without draped net introduced in Year 3, installed annually, and replaced in Year 17. Only in scenario 5 is the net replaced twice. The inputs for yield and packout are estimates based on the potential of such an orchard. A full-bearing yield of 120 t/ha is used, but the packout estimates are the more optimistic ones. In scenarios 6 and 7 we add one (scenario 6) or two (scenario 7) severe hail or sunburn events, resulting in substantially decreased fruit quality and thus income in that year for the open orchard: OR = 80%; Class 1 = 30%; Class 2 = 30%; Class 3 = 40%. For the netted orchard we assumed some additional damage but less so: OR = 95%; Class 1 = 50%; Class 2 = 30%; Class 3 = 20%.

The budgeting of lifetime costs and income of the second draped netting trial (‘Golden Delicious’, Southfield, EGVV) was not conducted. The primary reason was our decision that the Dutoit Agri enterprise model cannot be simply applied to a farm with a very different context and cost-income structure. A significant adjustment of the model would have to be undertaken and this was not feasible in the timeframes of the project. It would have to involve the farm management and it cannot be assumed that the necessary information would necessarily be shared with the researchers.

Table 7 Description of the scenarios used to run the orchard level financial model comparing the use of draped nets versus no nets in 'Golden Delicious Reinders' apple orchards.

	Period	Net installed first time	Net replaced	Severe hail/ sunburn event	Yield	Quality: OR	Quality: Class 1	Quality: Class 2	Quality: Class 3
Scenario 1	2009-2034	2019	no	No	Actual data from 2009-2020; thereafter 120t/ha	Estimated: 0%, 70%, 80%, 80%, 92%, thereafter 92% (open) and 98% (net)	Estimated: 0%, 0%, 20%, 40%, 50%, thereafter 50% (open) and 55% (net)	Estimated: 0%, 70%, 60%, 40%, 23%, thereafter 23% (open). Net: 30% from 2020.	Estimated: 0%, 30%, 20%, 20%, 27%, thereafter 27% (open). Net: 15% from 2020.
Scenario 2	2009-2034	2019	no	No	Actual data from 2009-2020; thereafter 100t/ha	Estimated: 0%, 70%, 80%, 80%, 92%, thereafter 92% (open) and 98% (net)	Estimated: 0%, 0%, 20%, 40%, 50%, thereafter 50% (open) and 55% (net)	Estimated: 0%, 70%, 60%, 40%, 23%, thereafter 23% (open). Net: 30% from 2020.	Estimated: 0%, 30%, 20%, 20%, 27%, thereafter 27% (open). Net: 15% from 2020.
Scenario 3	2009-2034	2019	no	No	Actual data from 2009-2020; thereafter 120t/ha	Estimated: 0%, 70%, 80%, 80%, 92%, thereafter 92% (open) and 98% (net)	Estimated: 0%, 0%, 20%, 40%, 50%, thereafter 50% (open) and 55% (net)	Estimated: 0%, 70%, 60%, 40%, 23%, thereafter 15% (open). Net: 20% from 2020.	Estimated: 0%, 30%, 20%, 20%, 27%, thereafter 35% (open). Net: 25% from 2020.
Scenario 4	2020-2044	2022	2036	None (factored into pack out)	Theoretical: 0, 0, 25, 45, 65, 85, 100, 110, thereafter 120t/ha	Estimated: 0%, 70%, 80%, 80%, 92%, thereafter 92% (open) and 98% (net)	Open: 0%, 0%, 20%, 40%, 50%, thereafter 50%; Net: 0%, 0%, 23%, 45%, 55%, thereafter 55%	Open: 0%, 70%, 60%, 40%, 23%, thereafter 23%. Net: 0%, 70%, 60%, 40%, 30%, thereafter 30%	Open: 0%, 30%, 20%, 20%, 27%, thereafter 27%. Net: 0%, 30%, 17%, 15%, 15%, thereafter 15%
Scenario 5	2020-2044	2022	2030 and 2038	None (factored into pack out)	Theoretical: 0, 0, 25, 45, 65, 85, 100, 110, thereafter 120t/ha	Estimated: 0%, 70%, 80%, 80%, 92%, thereafter 92% (open) and 98% (net)	Open: 0%, 0%, 20%, 40%, 50%, thereafter 50%; Net: 0%, 0%, 23%, 45%, 55%, thereafter 55%	Open: 0%, 70%, 60%, 40%, 23%, thereafter 23%. Net: 0%, 70%, 60%, 40%, 30%, thereafter 30%	Open: 0%, 30%, 20%, 20%, 27%, thereafter 27%. Net: 0%, 30%, 17%, 15%, 15%, thereafter 15%
Scenario 6	2020-2044	2022	2036	Event in 2029	Theoretical: 0, 0, 25, 45, 65, 85, 100, 110, thereafter 120t/ha	Estimated: 0%, 70%, 80%, 80%, 92%, thereafter 92% (open) and 98% (net)	Open: 0%, 0%, 20%, 40%, 50%, thereafter 50%; Net: 0%, 0%, 23%, 45%, 55%, thereafter 55%	Open: 0%, 70%, 60%, 40%, 23%, thereafter 23%. Net: 0%, 70%, 60%, 40%, 30%, thereafter 30%	Open: 0%, 30%, 20%, 20%, 27%, thereafter 27%. Net: 0%, 30%, 17%, 15%, 15%, thereafter 15%
Scenario 7	2020-2044	2022	2036	Events in 2029 and 2035	Theoretical: 0, 0, 25, 45, 65, 85, 100, 110, thereafter 120t/ha	Estimated: 0%, 70%, 80%, 80%, 92%, thereafter 92% (open) and 98% (net)	Open: 0%, 0%, 20%, 40%, 50%, thereafter 50%; Net: 0%, 0%, 23%, 45%, 55%, thereafter 55%	Open: 0%, 70%, 60%, 40%, 23%, thereafter 23%. Net: 0%, 70%, 60%, 40%, 30%, thereafter 30%	Open: 0%, 30%, 20%, 20%, 27%, thereafter 27%. Net: 0%, 30%, 17%, 15%, 15%, thereafter 15%

CHAPTER 4: RESULTS AND DISCUSSION – FIXED NETTING TRIAL

4.1 ORCHARD MICROCLIMATE

4.1.1 Orchard microclimate

4.1.1.1 Solar radiation

Typical trends in the daily total solar radiation for the control orchard and under the fixed nets are shown in Figure 43. These data are for two seasons namely, the 2018-2019 (a) and the 2019-2020 season (b). Data for the first season were not continuous due to internal datalogger battery failure for the fixed nets. This resulted in the loss of data at the start of the campaign for the whole month of October 2018. There was also an extended period of data loss from around 05 March 2019 to end of May 2019 for the control weather station in the open orchard due to the malfunctioning of the radiation sensor. The second season (October 2019 to June 2020) had a more continuous data set as shown in Figure 4.1b. As expected, data from both seasons showed a significant reduction in the radiation intensity under the white fixed nets. Data from the open and the nets were strongly linearly related with a slope of about 0.75 in the first season (Figure 44a) and 0.88 in the second season (Figure 44b). This suggests reductions in the radiation intensity under the fixed nets of about 25 and 12%, respectively.

The cause of the disparity in the attenuated radiation between the two seasons is unclear. But the quality of the data in the first season, which had large gaps, may be a contributory factor. Lack of levelness in the radiation sensors may also have played a part in the first season. The radiation sensors were cross calibrated against each other which eliminated systematic differences in sensor readings as a cause for the differences. Peak radiation in the open orchard was lower in the first season at about 29 MJ m^{-2} d^{-1} compared to almost 33 MJ m^{-2} d^{-1} in the second season. The corresponding maximum daily solar radiation under the nets were about 21 MJ m^{-2} d^{-1} in the first season and almost 29 MJ m^{-2} d^{-1} in the second. Owing to these issues, further analysis of effects of fixed nets on solar radiation will focus on the second season. A detailed discussion of the seasonal changes in the radiation differences between the open and netted orchards are discussed in the next sections.

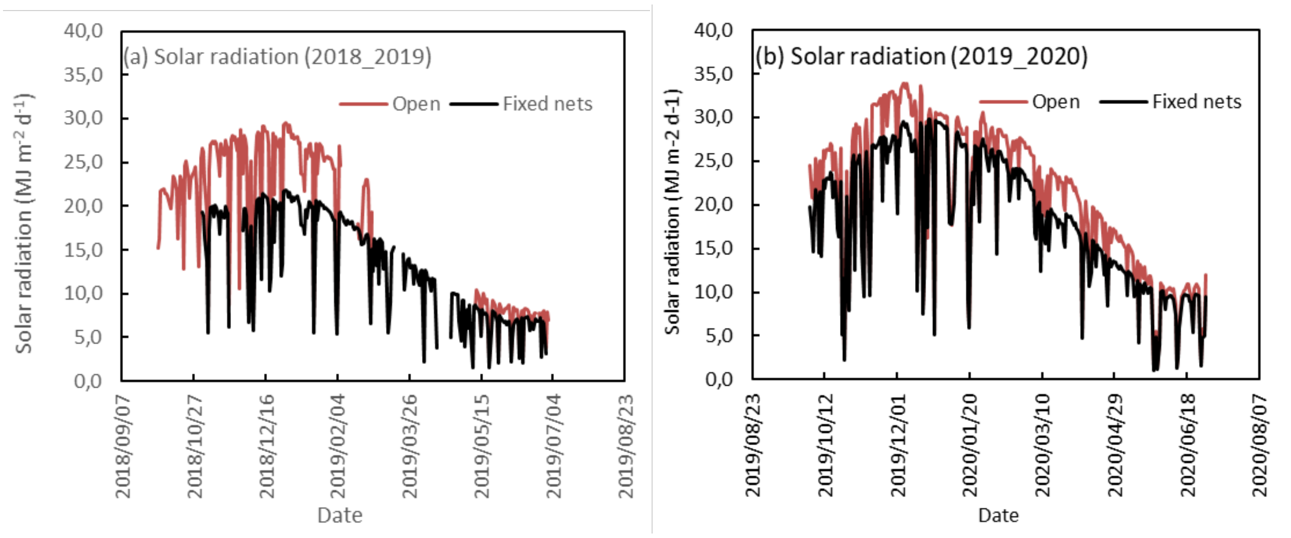


Figure 43 Daily solar radiation in the open and under fixed nets during: (a) the 2018-2019 season, and; (b) 2019-2020 season

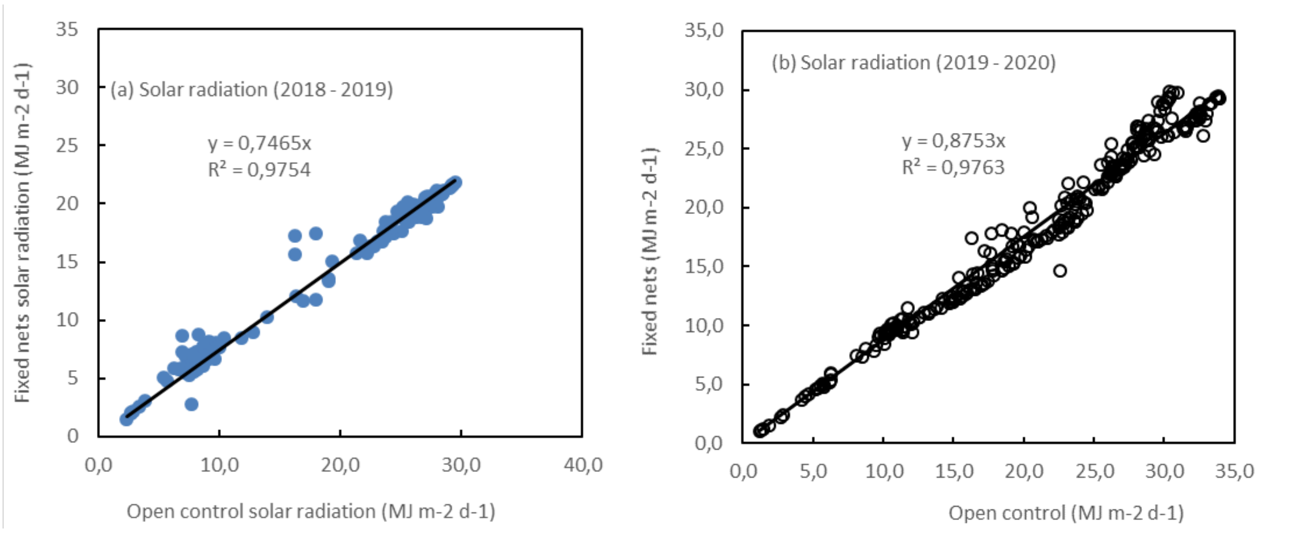


Figure 44 Relationship between the daily total solar radiation in the open and for the fixed nets during (a) the 2018-2019 and (b) 2019-2020 growing seasons.

4.1.1.2 Air temperature, relative humidity, and vapour pressure deficit

The effect of the fixed nets on the temperature and relative humidity under the nets was complex (Figure 45). There was no significant difference in the maximum temperature in the 2018-2019 season, while the maximum temperature was about 2% higher under nets in the 2019-2020 season. The minimum temperature was similar between the two treatments in 2018-2019 while it was about 3% higher in the open. There were no significant differences in the maximum relative humidity between the two treatments in both years while there was between 1 and 3% difference in the minimum relative humidity. The error margins for relative humidity measurements are typically in the range ± 5% (Monteith and Unsworth, 1990). This means that the differences obtained between the open and fixed nets treatments are within the error margins of the measuring devices. Differences in the VPD are also quite likely very small.

The observed inconsistent temperature differences are also contrary to results that have been reported in other studies. For example, Shahak et al. (2004) reported a 3-6ºC lower air temperature under nets compared to the control. A study on plum orchards by Malik (2020) also in the Western

Cape Province, using a similar 20% white flat shade net found a mean reduction in air temperature of ca. 1ºC under the net compared to the open orchard. The lack of a clear difference, compared to previous studies from other climatic regions, is possibly due to: 1) the small size of the netted area that reduced the fetch of the orchard almost creating a clothesline effect, 2) the net structure having open sides which allowed mixing of the air outside and inside the nets, 3) the climatic characteristics of the region, and/or; 4) the positioning of the sensor above the tree canopy, close to the net (Solomakhin and Blanke, 2010a).

Middleton and McWaters (2002), Rigden (2008) and Szabó et al. (2021) found an increase in relative humidity of the air under a fixed net by 10-15%, with smaller increases of 2-9% reported by Iglesias and Alegre (2006), Solomakhin and Blanke (2010a) and Bosco et al.(2018). This was different to our study where relative humidity was not significantly altered under the net (within-canopy at 2 m height) compared to the open (ca. 3% difference). Similarly, no differences in RH were found in the apple production region of Washington State, USA (Kalcsits et al., 2017). This result can possibly be explained by the ready mixing of the air under the net due to the open sides of the netting structure. Stamps (2009) explained that RH is often higher under nets, and more so if the sides are closed or the net thread density is high. This is because air movement is restricted, and the water vapour transpired by the trees is not mixed with outside dry air as much as if there were no net covering. The positioning of the RH sensor may also explain differences between studies (Lakatos et al., 2011).

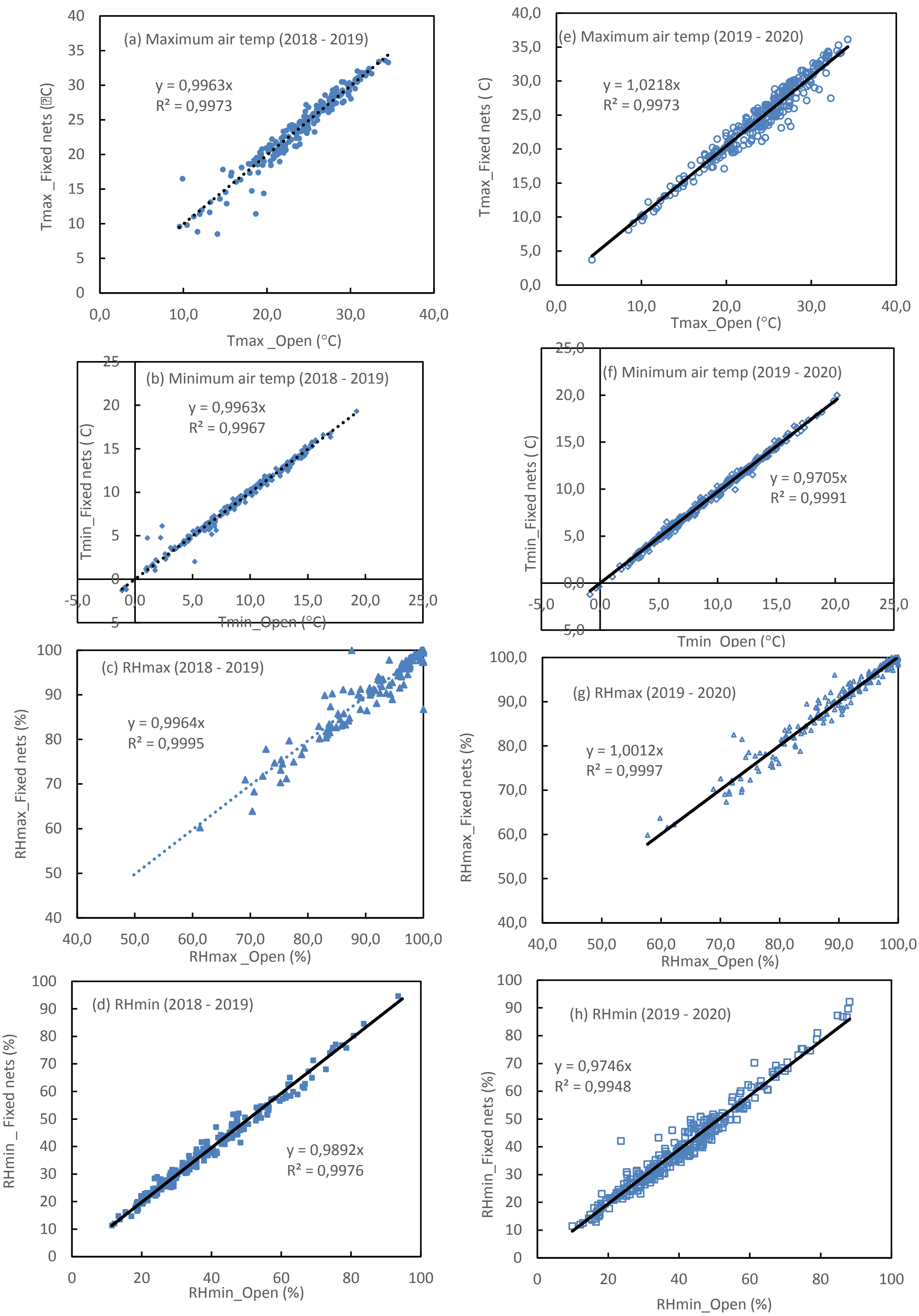


Figure 45 Comparison of the microclimate in the open and under fixed nets during the 2018-2019 season (a-d), and; 2019-2020 season (e-h).

4.1.1.3 Wind speed

Figure 46 shows wind speed differences of only between 5 and 6% between the open and fixed net treatments. This is very low compared to previous studies where nets covering all sides of the orchard or screenhouse, or nets with a high thread density resulted in the wind speed being reduced by more than 50% (Middleton and McWaters, 2002; Möller et al., 2004; McMahon et al., 2013).

A reduction of up to 36% in the early stages of the first season was similar to the reduction of 40% reported by Kalcsits et al. (2017), and McCaskill et al. (2016) who measured a 22% reduction at 3 m height. Tanny et al. (2009) studied the effects of nets on the properties of wind and the canopy boundary layer of covered citrus and apple rows, and found that the nets act as a barrier to vertical air movement and this enhances atmospheric stability. They suggested that this may potentially reduce the atmospheric evaporative demand of trees under nets compared to the open.

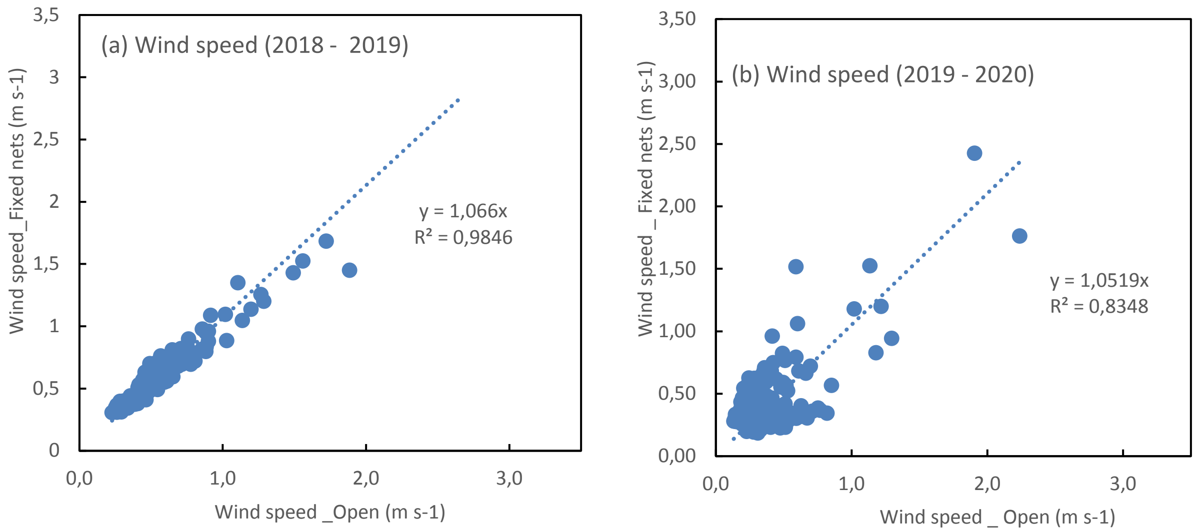


Figure 46 Effect of the fixed shade nets on the wind speed in (a) 2018-2019 and (b) 2019-2020.

Plots of differences in the daily weather variables inside and outside the fixed nets are shown in Figure 47 for the 2018-2019 season (a-d) and for the 2019-2020 season (e-h). It appears from the 2019-2020 season that the difference in the radiation intensity was smallest during the peak summer season (Figure 47e). The maximum air temperature was greater under the nets (Figure 47f) possibly because of the reduced air circulation. Consequently, the minimum relative humidity (Figure 47h) was also lower under the nets, being up to 7% lower than outside the nets. The minimum air temperature difference was less than 0.6°C in both seasons. Table 8 summarizes the seasonal differences while (Table 9) presents the monthly values for the 2019-2020 season when the data were more continuous.

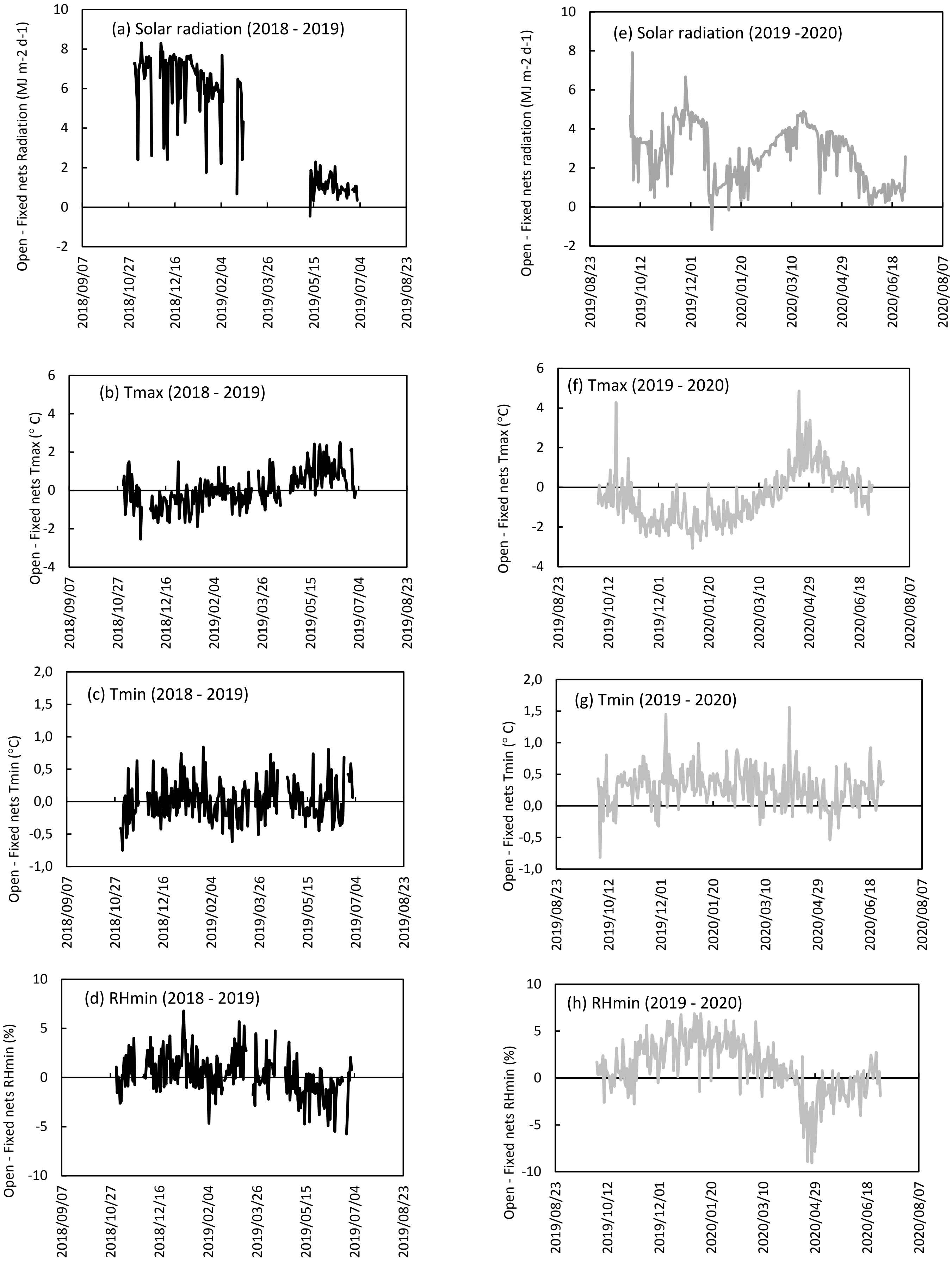


Figure 47 Daily differences between the solar radiation, Tmax, Tmin, and RHmin for (a) 2018-2019 and (b) 2019-2020.

Table 8 Summary of the monthly differences between in weather variables in the open and under fixed nets. MAD represents the mean absolute difference, MxD represents the maximum difference for the month.

	Variable	**Tmax**		**Tmin**		**RHmax**		**RHmin**		**Rs**		**Wind speed**	
Season	**Month**	**MAD** (°C)	**MxD** (°C)	**MAD** (°C)	**MxD** (°C)	**MAD** (%)	**MxD** (%)	**MAD** (%)	**MxD** (%)	**MAD** ($MJ/m^2/d$)	**MxD** ($MJ/m^2/d$)	**MAD** (m/s)	**MxD** (m/s)
2018-2019	October												
	November	0.76	2.54	0.29	0.75	1.07	6.10	1.32	4.01	6.75	8.31	0.08	0.17
	December	0.82	1.68	0.21	0.63	0.22	1.90	1.69	4.25	6.51	7.86	0.08	0.17
	January	0.60	1.89	0.25	0.84	1.19	7.00	1.85	6.78	6.17	7.26	0.11	0.21
	February	0.37	1.25	0.21	0.62	1.09	5.60	1.26	4.67	4.96	12.60	0.08	0.20
	March	0.54	1.31	0.22	0.51	0.47	3.80	1.85	5.68	12.75	16.22	0.03	0.11
	April	0.58	1.63	0.28	0.73	1.16	6.42	1.56	4.74	9.61	12.68	0.06	0.24
	May	1.02	2.42	0.19	0.74	1.12	4.30	1.55	4.74	2.62	9.23	0.06	0.14
	June	0.95	2.50	0.30	0.81	0.94	5.03	1.80	5.74	0.98	2.06	0.07	0.44
	Average	**0.71**	**1.90**	**0.24**	**0.70**	**0.91**	**5.02**	**1.61**	**5.08**	**6.29**	**9.53**	**0.07**	**0.21**
2019-2020	October	0.75	4.28	0.31	0.82	0.75	3.85	1.75	3.85	2.89	7.92	0.20	0.39
	November	1.52	2.49	0.37	0.79	0.90	3.82	2.50	3.82	4.00	6.67	0.08	0.16
	December	1.56	2.45	0.45	1.45	1.11	6.70	3.69	6.70	2.71	4.86	0.08	0.16
	January	1.66	3.08	0.34	0.99	0.78	2.92	3.96	2.92	1.60	3.03	0.08	0.15
	February	1.38	2.38	0.43	0.89	1.58	10.21	3.22	10.21	2.90	3.90	0.28	0.57
	March	0.62	1.64	0.29	0.68	0.92	4.69	1.63	4.69	4.05	4.91	0.24	0.47
	April	1.33	4.86	0.33	1.56	0.91	4.90	2.81	4.90	3.24	4.14	0.19	0.37
	May	0.99	2.35	0.22	0.67	0.79	7.82	1.61	7.82	1.77	3.47	0.14	0.28

	June	0.52	1.37	0.29	0.92	0.60	2.60	1.11	2.60	0.86	2.58	0.17	0.33
	Average	**1.15**	**2.77**	**0.34**	**0.97**	**0.93**	**5.28**	**2.48**	**5.28**	**2.67**	**4.61**	**0.16**	**0.32**

Table 9 Summary of monthly weather variables (with standard errors) for the open and net treatment at the 'Rosy Glow' fixed net site in 2019-2020.

Month	**Rs (MJ/m²/d)**				**Tmax (°C)**				**Tmin (°C)**				**RHmin (%)**			
	Open	**SE**	**Net**	**SE**	**Open**	**SE**	**Net**	**SE**	**Open**	**SE**	**Net**	**SE**	**Open**	**SE**	**Net**	**SE**
October	21,3	1,17	18,8	1,15	31,8	1,04	32,7	1,13	1,7	0,49	1,5	0,56	10	3,29	12	3,53
November	27,7	1,18	23,9	0,99	32	0,72	34,3	0,73	4	0,51	3,6	0,49	16	2,49	13	2,41
December	27,6	1,44	24,5	1,28	31,8	0,81	33,8	0,90	3,6	0,52	3,2	0,51	16	2,38	14	2,40
January	25,5	1,07	23,4	0,98	34,3	0,73	36,1	0,79	6,8	0,56	6,6	0,56	29	2,05	26	2,07
February	26,8	0,43	23,7	0,41	33,5	0,56	35,2	0,55	8,2	0,45	8,1	0,40	15	2,08	16	1,86
March	22,2	0,43	17,8	0,37	33,4	0,56	34	0,60	6,4	0,57	5,9	0,57	26	1,55	29	1,52
April	17,3	0,61	13,6	0,48	32,3	0,76	27,5	0,70	3,6	0,51	3,4	0,50	18	2,77	22	2,79
May	11,4	0,76	9,1	0,60	30,9	1,03	29	0,98	2,4	0,39	1,8	0,42	16	3,88	18	3,95
June	8,8	0,52	7,7	0,48	26,7	1,05	25,4	1,03	-0,8	0,53	-1,2	0,53	18	3,64	21	3,68

	U (m/s)				ET_o (mm)				VPD (kPa)				Rainfall (mm)
	Open	**SE**	**Net**	**SE**	**Open**	**SE**	**Net**	**SE**	**Open**	**SE**	**Net**	**SE**	
October	0,5	0,06	0,3	0,01	3,3	0,16	3,0	0,16	1,0	0,06	1,0	0,06	90,9
November	0,3	0,02	0,2	0,01	4,4	0,17	4,0	0,15	1,1	0,05	1,2	0,05	8,9
December	0,3	0,02	0,3	0,01	4,6	0,23	4,3	0,21	1,0	0,05	1,1	0,06	66
January	0,3	0,02	0,3	0,02	4,5	0,18	4,4	0,18	1,0	0,05	1,2	0,06	51
February	0,3	0,06	0,2	0,02	4,5	0,09	4,5	0,10	1,3	0,06	1,5	0,06	5,8
March	0,3	0,01	0,2	0,02	3,4	0,09	3,1	0,09	1,0	0,05	1,1	0,05	10,4
April	0,3	0,02	0,2	0,03	2,1	0,08	2,0	0,08	1,0	0,05	0,9	0,05	92,9
May	0,3	0,04	0,2	0,03	1,2	0,05	1,2	0,06	1,0	0,06	0,9	0,06	92,4
June	0,3	0,08	0,4	0,07	1,0	0,07	1,0	0,04	0,7	0,06	0,7	0,05	164,3

4.1.2 Interception of photosynthetically active radiation

In the fixed net trial, one tree was selected for monitoring in the middle of the orchard and this tree was outside the shade nets. This is hereafter called the “outside control”. Five, line quantum sensors were installed at different levels in the canopy of this tree. The topmost sensor (Sensor #1) was located above the canopy and it measured the incident PAR with no nets. Sensor #2 was positioned in the canopy, but about 1.0 m below Sensor #1. Sensor #3 was positioned at the lower portion of the canopy about 1.0 below Sensor #2. Sensor #4 was positioned in the open space right underneath the canopy and outside the foliage. Sensor #5 was positioned at the same level as Sensor #4, but it was in the open space between the tree rows. The same setup was repeated for the tree under the fixed nets treatment with the topmost sensor referred to as the “fixed net control sensor”.

Three scenarios of the fractional intercepted PAR are discussed for fixed nets on a typical clear day on 20 December 2019 (Figure 48a). The data was recorded hourly from 08h00 to 18h00. Scenario 1 considers only the radiation for the control treatment. Here we calculated the fractional intercepted PAR for Sensors 2 to 5 expressed as a ratio of the outside control (i.e. Sensor 1). These data are displayed in Figure 48b. In Scenario 2, we calculated the fractional intercepted PAR for Sensors 2 to 5 under the fixed netting (Figure 48c). The third scenario (Scenario 3) compared the intercepted fractional PAR as ratios of Sensor 1 under the fixed nets (Figure 48d). For all the 3 scenarios, it was clear that the intercepted fractional PAR varied throughout the day as the sun angle changed. The highest fractional PAR intercepted was highest at midday when the sun was overhead, but much of the variation reflected the exposure of the sensor in the canopy.

In Scenario 1 (control treatment), the PAR sensor located about 1.0 m from the top of the canopy (blue line in Figure 48a), had the highest fractional interception which ranged from about 40% in the morning and late afternoon peaking to around 95% around midday. The sensor at the base of the canopy (Sensor 3) and that in the inter-row spacing also had high interception rates ranging from about 10% when fully shaded in early morning and evening peaking to between 60 and 80% around noon. The sensor which was directly underneath the canopy (Sensor 4) and hence had the greatest shading, intercepted the least radiation ranging from about 10% with a maximum of only about 30% of the radiation from the outside control.

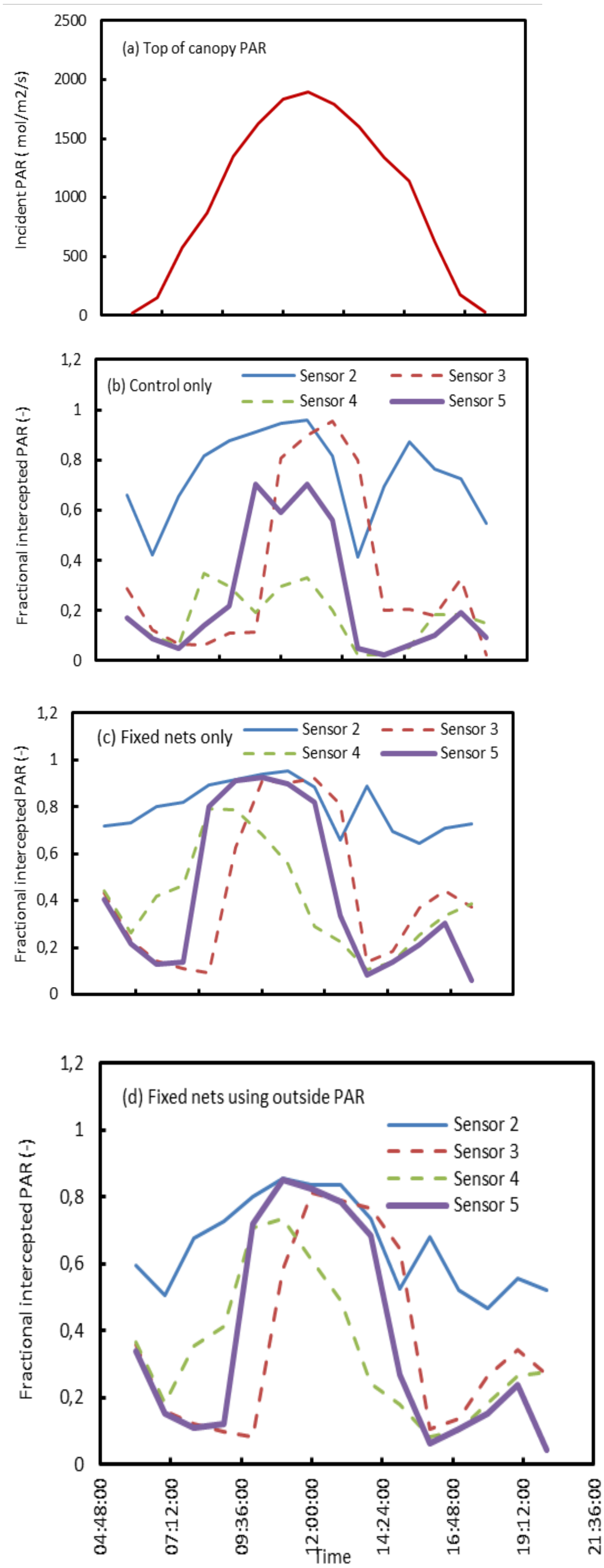


Figure 48. Fractional PAR intercepted under the fixed nets ('Rosy Glow') on a typical clear day in December.

For Scenario 2 for which we use data from the fixed nets treatment only, the fraction of intercepted PAR calculated as the ratio of Sensor 2 to Sensor 1 (fixed net control) was similar to that for the control treatment described above (Figure 48c). On the orchard floor under the fixed nets, the intercepted radiation varied from about 5 to 80% depending on the time of day and the exposure of the PAR sensors. For Scenario 3, where we calculate the ratio of the within canopy sensors under fixed nets (Sensors 2-5) to the control sensor at the top of the canopy outside the nets, the results are shown in Figure 48d. Sensor 2 under the fixed nets intercepted between 50 and 80% of PAR around noon which was lower than that of the other two Scenarios described earlier. The trends and magnitudes of the intercepted radiation fraction on the orchard floor were similar to those reported for Scenario 2.

4.2 SOIL PROPERTIES, SOIL WATER CONTENT AND IRRIGATION

4.2.1 Soil physical properties

The soil profile up to 1.2 m deep in the open (control) and under the fixed nets contained less than 8.6% clay and silt and were classed according to *particle size* (Soil Classification Working Group, 1991) as sand (Appendix G: Table 55; Figure 49). Although the fine sand fraction in the open and under net was comparable (on average 37.7%), the former section had 5.6% less medium and 6% more coarse soil than the latter. Under the fixed net the fine and medium sand fraction tended to decrease with depth, whereas coarse sand increased (data not shown). There was no specific trend regarding texture in the open except for an increase in stone content with depth. The soils had less than 2% stone. The water holding capacity of the soil up to 1.2 m depth was according to texture estimated by Bemlab as 98.2 and 94.3 mm m^{-1} for the open and netted orchard sections, respectively. This is somewhat higher than the 69.1 and 67.8 mm m^{-1} estimated from soil texture according to Saxton et al. (1986) for the respective soils.

Bulk density ranged between 1.42 and 1.7 in the ridge, 1.48 and 1.8 in the tractor track and 1.52 and 1.66 g cm^{-3} in the cover crop area (Figure 50). There were minor differences between the soil bulk density in the control and netted area, except at 1 m depth where the netted ridge and cover crop areas had significantly higher bulk density compared that in the open area. Bulk density tended to increase with depth in the ridge and was notably higher in the tractor track at the 200 mm depth than in the ridge and cover crop.

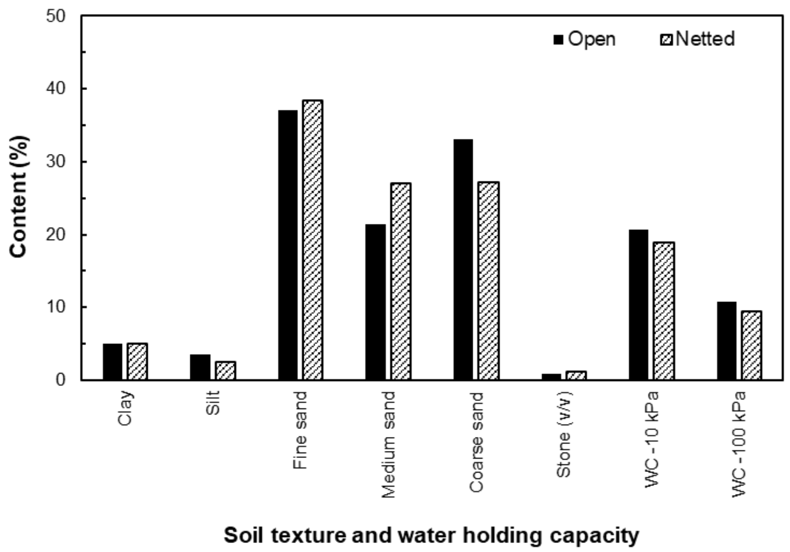


Figure 49. Soil particle size distribution and water content (WC) at -10 kPa and -100 kPa for the open (control) and netted areas in the 'Rosy Glow' orchard at Paardekloof in 2018-2019. Soils were sampled in the ridge and data averages represent the soil profile up to a 1.2 m depth.

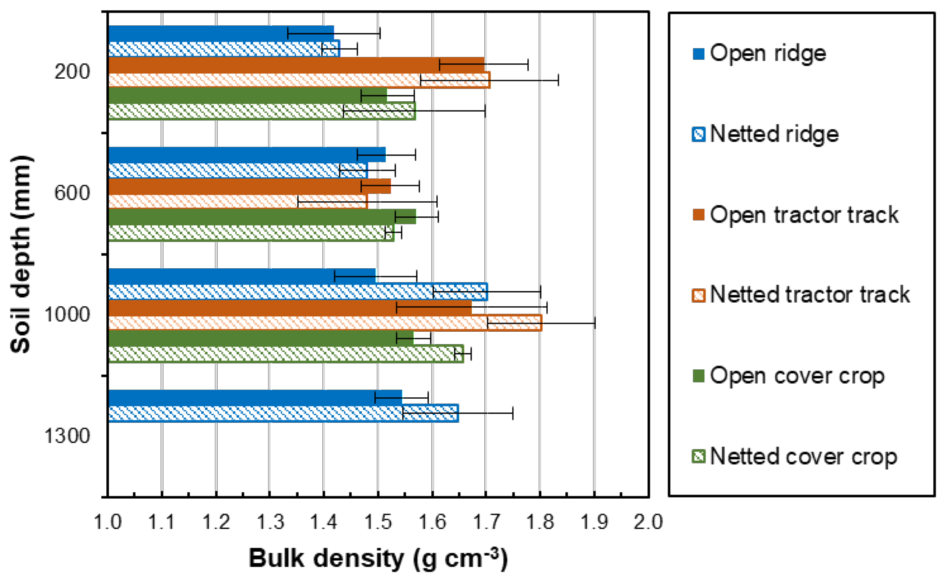


Figure 50. Bulk density of sandy soil at the 200, 600, 1000 and 1300 mm depths in the ridge, tractor track and cover crop areas, respectively, of the control and netted 'Rosy Glow' orchard at Paardekloof in 2018-2019.

Almost constant wet conditions in the orchard during the 2018-2019 season did not allow sampling for a range of wet and dry samples and prevented establishment of the *in situ* soil water retention curves. Soil water retention curves estimated from soil texture according to Saxton et al. (1986) indicated no real difference between depths (data not shown) and that for the open and netted parts of the orchard (Figure 51).

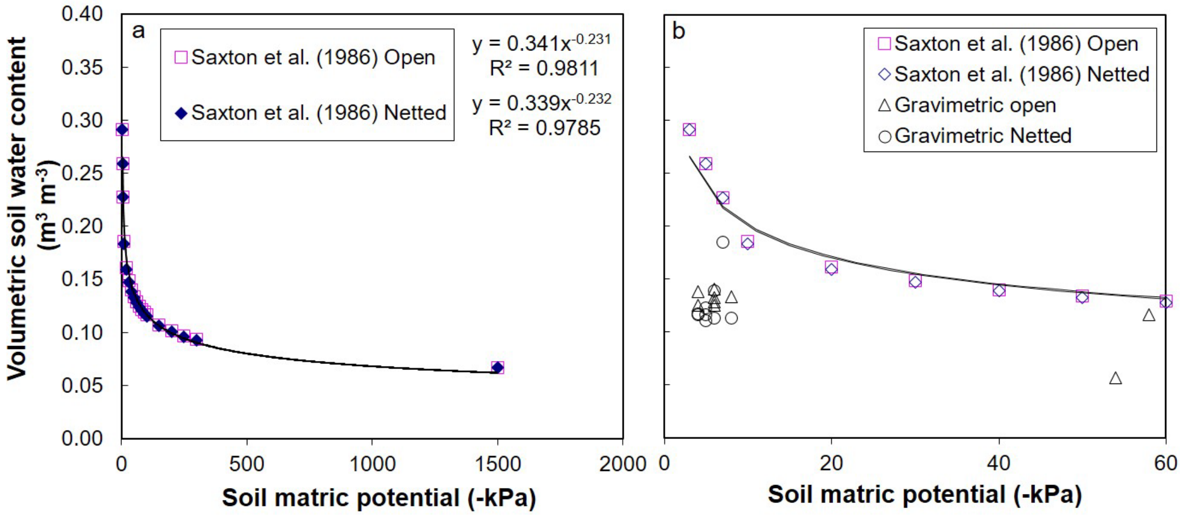


Figure 51. Comparison of a) soil water retention curves of a 1.2 m sandy soil profile in the open and under net at Paardekloof and b) estimated curves with gravimetric samples taken to establish in situ retention curves. The soil water retention curves were estimated from profile averaged soil texture according to Saxton et al. (1986).

The values of one set of gravimetric samples taken in the orchard for in situ soil water retention curves compared poorly with the estimated soil water retention properties (Figure 51b). According to the commercial laboratory, soil water retained at -10 kPa was 20.6% in the open and 18.9% for the netted section, which compared well with Saxton et al. (1986). The soil water holding capacity between -10 and -100 kPa was estimated by the commercial laboratory from texture as 98.2 and 94.3 mm m^{-1} for the open and fixed net orchard sections, respectively. According to Saxton et al. (1986) these amounts were 69.1 and 67.8 mm m^{-1}, and the plant total available water between -10 and -1500 kPa for the open and netted sections, respectively, 118.2 and116.2 mm m^{-1}.

With regard to establishment of *in situ* soil water retention curves, the majority of samples taken at the ‘Rosy Glow’ orchard (n=90) were in the wet range (i.e. <-10 kPa). Further sampling representative of the dry range was necessary before the retention curves could be finalised, but the high irrigation frequency applied in the orchards prevented collection of such samples. The actual volumetric soil water content compared in general poorly with the soil water retention properties estimated according to Saxton et al. (1986) (Figure 52).

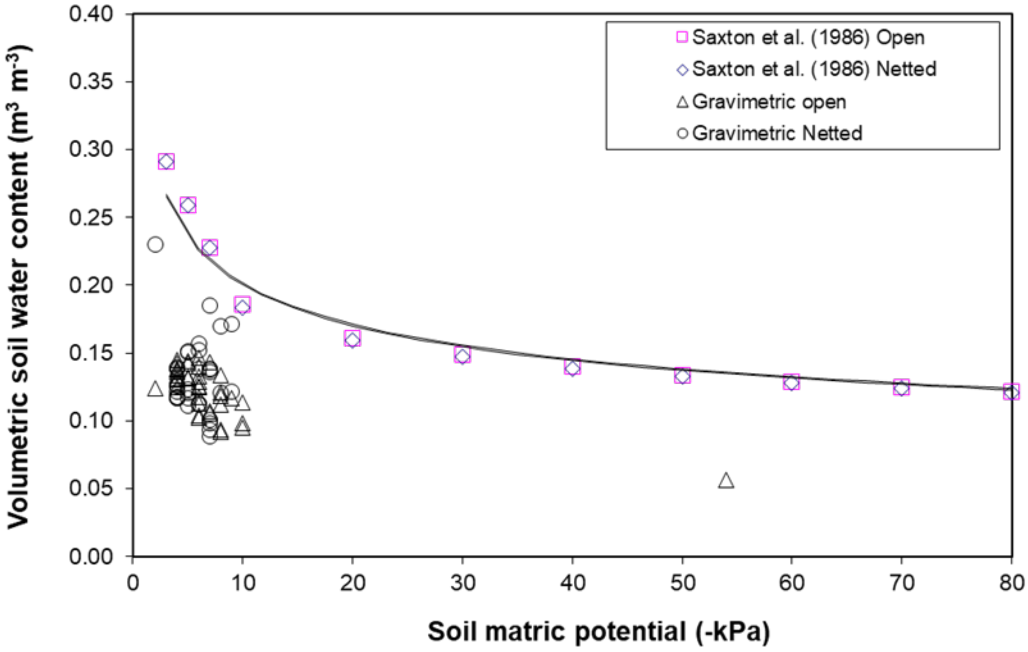


Figure 52 Comparison of estimated soil water retention curves of a 1.2 m sandy soil profile in the open and below net at the 'Rosy Glow' fixed net orchard, with gravimetric samples taken to establish in situ retention curves. The soil water retention curves were estimated from profile averaged soil texture according to Saxton et al. (1986).

4.2.2 Soil water content dynamics and irrigation: 2018-2019

Continuously wet conditions in the orchard during the 2018-2019 season prohibited establishment of calibration relationships for the soil water content sensors. Only general trends in volumetric soil water content, based on the factory calibration, are therefore discussed in this section. The deepest layer in the ridge indicated over-irrigation at several times during February to June both in the open (Figure 53a, Figure 53d) and netted (Figure 54a, Figure 54d) sections of the orchard.

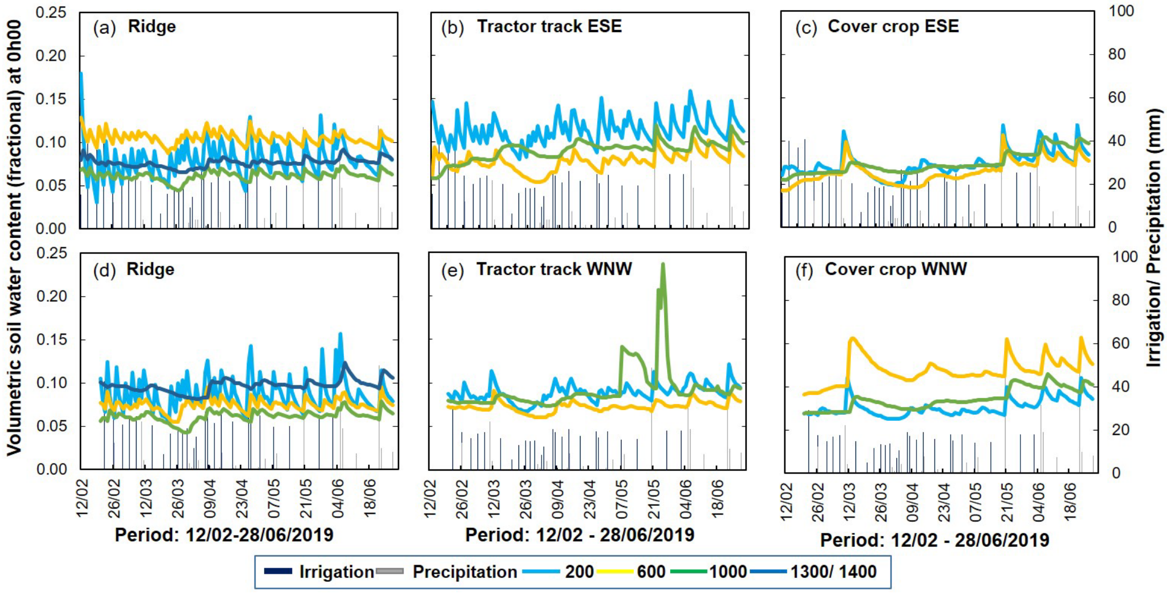


Figure 53 Soil water dynamics for the ridge (a & d), tractor track (b & e) and cover crop (c & d) on the east-south-east (b & c) and west-north-west (e & f) sides of the tree row in the open section of the orchard from February until June 2019. Volumetric soil water content for the different soil depths (mm) is based on the sensor factory calibration. The deepest soil layer in (c) and (d) is 1300 and 1400 mm, respectively.

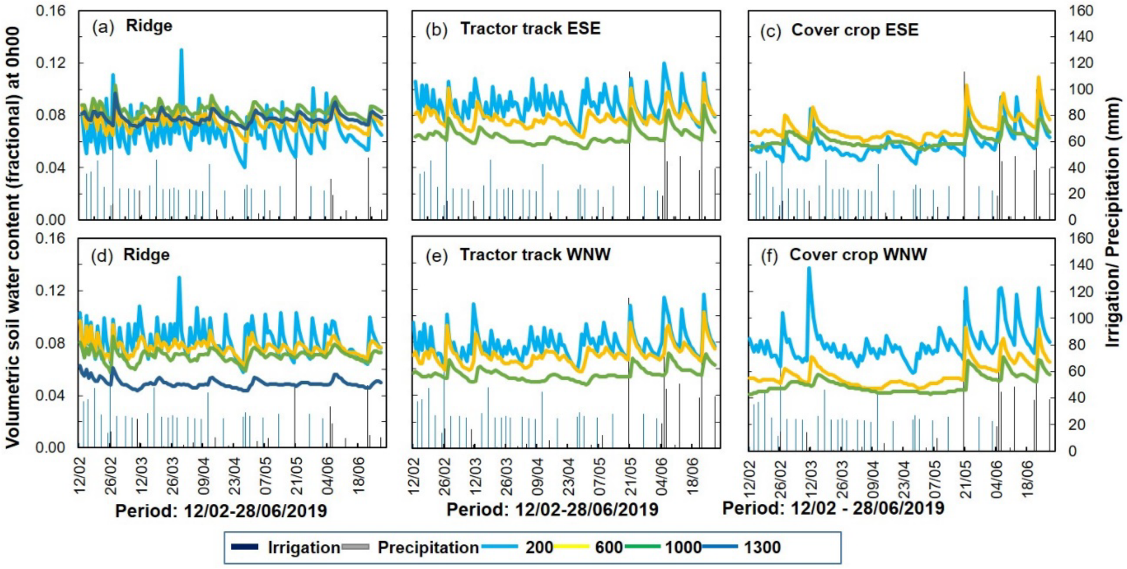


Figure 54 Soil water dynamics for the ridge (a & d), tractor track (b & e) and cover crop (c & d) on the east-south-east (b & c) and west-north-west (e & f) sides of the tree row in the fixed net section of the orchard from February until June 2019. Volumetric soil water content for the different soil depths (mm) is based on the sensor factory calibration.

Profile averaged soil water content in general tended to follow similar trends in the open and below net, except for a period during March 2019, when the soil water content in the ridge of the open area tended to decrease (Figure 55a). Soil water content on the whole tended to increase towards the end of the season in the tractor track and/ or cover crop area in both the open and netted orchard sections (Figure 55a & Figure 55b).

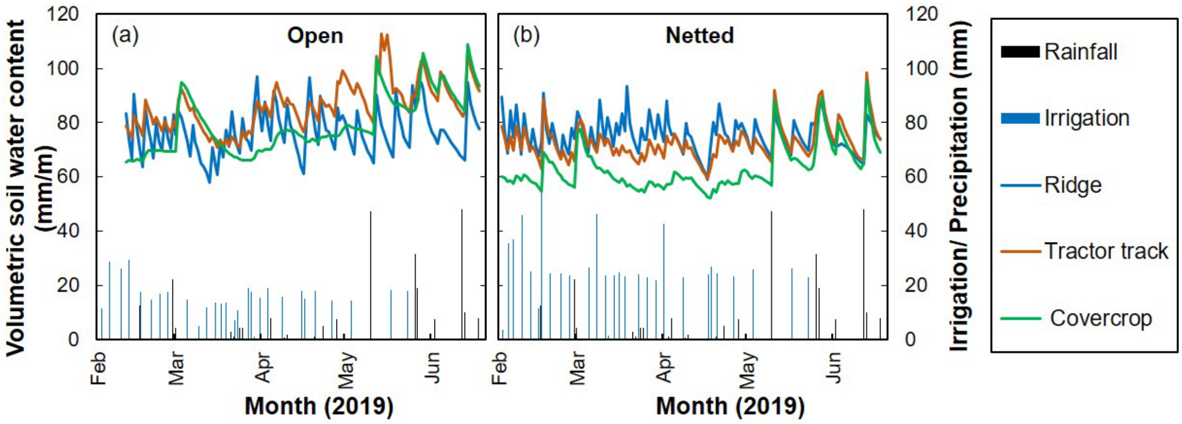


Figure 55 Comparison of volumetric soil water content for the (a) open and (b) fixed net sections of the orchard at Paardekloof from February until June 2019. Volumetric soil water content is based on the sensor factory calibration.

A higher amount of irrigation applied to the netted compared to the open section may partially be attributed to pressure differences in the irrigation system (Figure 55). Several orchards having different irrigation schedules are irrigated from the same main line, which may affect the line pressure and therefore the application rate of emitters. We here present some initial results for soil temperature at 200 mm depth for February 2019 (Figure 56). At midday, soil temperatures below the net varied between 7°C and 21.3°C, and in the open between 7.5°C and 21.1°C. There was no significant difference in the maximum soil temperatures for the ridge, tractor track and cover crop below the net compared to the open nor between these orchard areas. The maximum temperature was on average 20.8°C for the ridge and tractor track, and 21.2°C for the cover crop area. Prins (2018) reported slightly elevated soil temperatures under nets; we could not confirm this in our study.

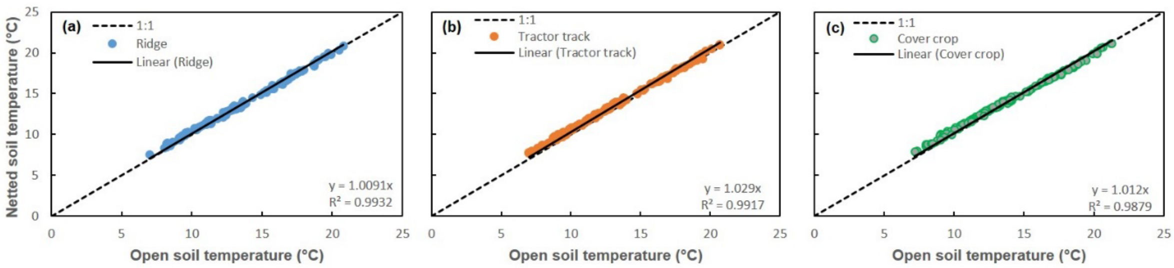


Figure 56 Comparison of CS650 soil temperature at 200 mm depth between below the net and in the open, in the ridge (a), tractor track (b) and cover crop (c) during February 2019.

4.2.3 Soil water content dynamics and irrigation: 2019-2020

Comparison of volumetric soil water content calculated from the CS650 dielectric permittivity (K_a) using the manufacturer's calibration and actual soil water content at comparable K_a values for the 200 mm depth indicated that the former in general underestimated the volumetric soil water content (Appendix F: Figure 141). Gravimetrically sampled volumetric soil water content was compared to the CS616 soil water content sensor period (μs) for orchard areas combined (ridge, tractor track, cover crop) and over measurement depths (220, 600, 1000, 1300 mm) per soil water balance site (C4, C10, N4, N8) for the open and fixed net sections of the orchard to establish if calibration relationships could be combined (Appendix F: Figure 142, Table 53). The *CS616 in situ calibration* statistics for sensors at each soil water balance site at the 'Rosy Glow' orchard (Appendix F: Table 53) indicated that calibrations between gravimetrically determined volumetric soil water content and K_a or CS616 period obtained accuracy equal to or better than the 2.5% indicated by the manufacturer with the highest error of the estimate being 1.4%. The K_a values ranged between 2.5 and 6.9 and the period values were restricted to the low range between 17 and 23. Outliers removed were attributed to variation in the spatial distribution of soil water along the length of the sensor prongs and/or variation in stone content of the sampled area vs sensor location.

Soil water dynamics for the different orchard areas showed for the control treatment that soil water content in the ridge, tractor track and cover crop areas followed similar trends until 15 August 2019 after significant rainfall events occurred at the beginning of the season (65 mm and 75 mm on 19 and 23 July 2019, respectively) (Figure 57a). The soil profile in all orchard areas became drier towards 7 October after which the soil water in the ridge and tractor track were again replenished by rainfall (c. 5 mm) and presumably by irrigation (no logged record).

The soil water content in the ridge in general remained high throughout the season until mid-April (Figure 57a). However, there were three periods (26/11-14/12/2019; 20-30/01/2020; 17/3-04/04/2020) where soil water content tended to decrease due to application of lower than average irrigation amounts (Table 10). The ridge reached its lowest soil water content late in the season on 24 May, but the soil profile was refilled by significant rainfall on 25 May and 10 June. For the tractor track the soil water content trend fell below that for the ridge after 7 October 2019 and it consistently remained that way until 6 April 2020. The lower soil water content trend for the tractor track followed that of the ridge closely until the end of January, after which the trend deviated and soil water content decreased more steeply until 6 April (Figure 57a).

For the cover crop area the soil water content consistently started to follow a drier trend compared to the ridge and tractor track areas after 15 August (Figure 57a). This may be due to water use by the cover crop, whereas water use for the ridge and tractor track only started later as full bloom for the 'Rosy Glow' trees occurred on 27 September 2019. The soil water content for the cover crop area responded to rainfall events but did not show a very clear response to irrigation. A once-off study on microsprinkler water distribution in the 'Rosy Glow' orchard indicated that 85%, 13% and 2% of the applied irrigation water falls on the ridge, tractor track and cover crop areas, respectively (data not shown). This may partially explain the different soil water content trends for the orchard areas. However, the apparent lack of response of the cover crop area to irrigation may be deceptive. Soil water dynamics for specific depths in the tractor track and cover crop area for the period 18 December until 19 January (data not shown) showed increasing soil water content trends. Irrigation amounts of on average 15 mm applied about every two days (Table 10) may have resulted in runoff from and/or lateral movement of water in the soil profile towards the tractor track and cover crop areas after irrigation events.

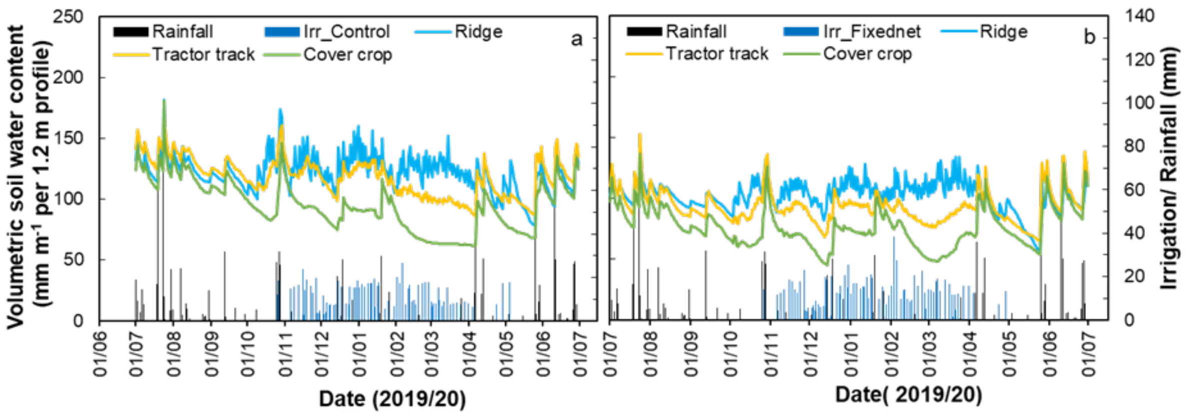


Figure 57 Soil water content (midnight) dynamics for the 'Rosy Glow' (a) control treatment and (b) fixed net treatment for ridge, tractor track and cover crop orchard areas for the period 01/07/2019-30/06/2020 during the 2019-2020 season.

Table 10 Monthly mean amount per irrigation event (±standard error or SE), number and interval of irrigations applied to the control and fixed net treatments at the 'Rosy Glow' orchard, Paardekloof during 2019-2020. Irrigation applied is indicated as mm per full surface area. Data are also indicated for selected periods.

Month/Period	**Irrigation amount (mm d^{-1})**				**Number (n)**		**Interval (d)**	
	Control		**Fixed net**		**Control**	**Fixed net**	**Control**	**Fixed net**
	Mean	**SE**	**Mean**	**SE**				
October	10.2	5.4	14.3	0.0	3	1	10.3	31.0
November	12.9	1.8	13.1	1.7	13	12	2.3	2.5
December	10.2	1.3	11.6	1.7	17	18	1.8	1.7
January	13.2	1.6	14.7	1.1	14	14	2.2	2.2
February	13.5	1.6	15.9	2.2	15	15	1.9	1.9
March	9.2	0.7	12.5	1.5	14	15	2.2	2.1
April	8.0	3.6	11.0	1.8	4	3	7.5	10.0
May	17.9	0.0	0.0	0.0	1	0	31.0	-
1/11-25/11/2020	15.0	1.7	15.0	1.7	9	8	2.8	3.1
26/11-14/12/2020	7.0	1.3	9.4	5.4	13	13	1.5	1.5
14/12/2019-19/01/2020	15.4	0.9	15.1	4.3	18	19	2.1	1.9
20-30/01/2020	5.7	1.8	10.9	2.1	4	4	2.8	2.8
06/03/2020-31/03/2020	9.6	0.9	12.3	4.0	11	13	2.4	2.0
17/3-04/04/2020	8.0	0.3	10.4	3.5	7	10	2.7	1.9

For the fixed net treatment the trend at the start of the season was more or less similar to that of the control with a definite drying trend starting for the cover crop area after 15 August 2019 (Figure 57b). The soil water content in the ridge tended to remain high except for one drying trend from 26

November until 14 December 2019 during which c. 9 mm water was applied per irrigation event instead of 15 mm as applied earlier in November. This drying trend also presented in the control treatment during this period. During April and May, as for the control, there was a definite drop in the fixed net treatment ridge soil water content, but the soil profile was refilled by rainfall near the end of May and at the beginning of June.

The tractor track also followed a similar, but drier trend relative to the ridge from 7 October. The cover crop area soil water content trend, albeit drier, resembled that of the tractor track and it is clear from the soil water content trends at different depths (data not shown) that the cover crop area soil water content was affected by irrigation events. This could have occurred due to lateral soil water movement or if higher than normal irrigation pressure affected the microsprinkler water distribution. Soil water tended to accumulate in the tractor track and cover crop areas from the 6th until the end of March. This is in contrast with the control treatment during this period where the tractor track still had a drying trend and low soil water content levels in the cover crop area leveled off. The control and fixed net treatments had a similar number of irrigations during this period, but microsprinklers for the fixed net area applied 29% more irrigation per irrigation event compared to those for the control area (12.3 mm vs 9.6 mm).

If soil water dynamics per soil depth are considered, the soil water content for the control treatment at the 200 mm depth tended to be higher than that at the 600 mm depth, but followed a more or less similar trend over the season in response to irrigation and rainfall (Figure 58a). The soil water content at 1 m depth was from the start of the season higher, but the trend was similar to that at the shallower depths, reflecting rainfall, irrigation and water use fluctuations. For the period 25 December 2019 until 21 January 2020 the soil water content at the 1 m depth reflected an accumulative trend, which coincided with a period of high irrigation application from 14 December 2019 until 19 January 2020 (Table 10).

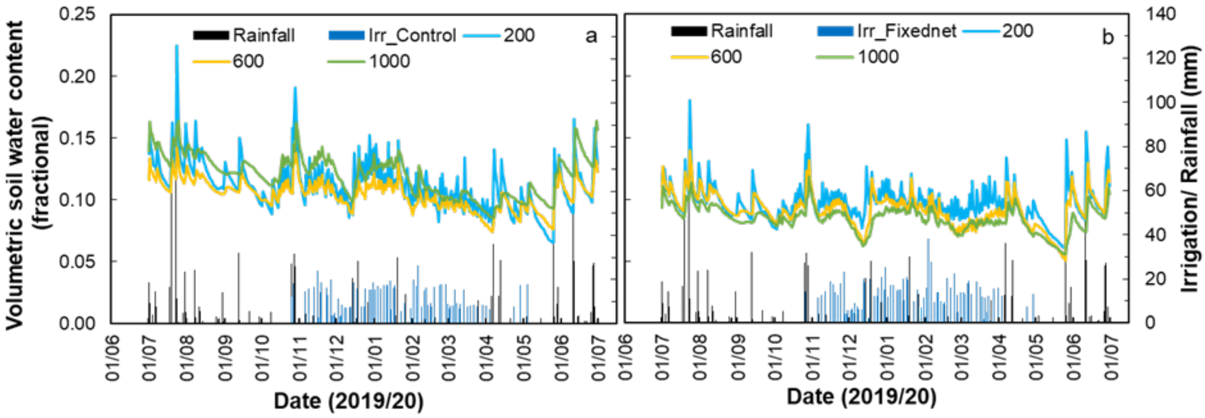


Figure 58 Soil water content (midnight) dynamics for the 'Rosy Glow' (a) control and (b) fixed net treatments averaged over orchards areas at the 200 mm, 600 mm and 1000 mm depths for the period 01/07/2019-30/06/2020 during the 2019-2020 season.

For the fixed net treatment, in general soil water content decreased with increasing depth from 200 to 600 mm to 1 m (Figure 58b). Trends over time reflected rainfall and irrigation events up to the 1 m depth. There were two periods during which soil water content at the 1 m and/or 600 mm depths did not follow the trend in the ridge and tended to gradually increase, i.e. from 9 November until 22 November 2019 and 1 March until 6 April 2020.

Soil water dynamics for the soil profile up to 1.2 m deep indicated that, despite differences in volumetric soil water content, seasonal trends in soil water content for the control and fixed net site were in general similar and reflected rainfall and irrigation events (Figure 59).

The exception was March until early April, during which the profile water content for the control had a decreasing trend and that for the fixed net an increasing trend. This difference can partially be attributed to less irrigation being applied to the control compared to the fixed net treatment (Table 10).

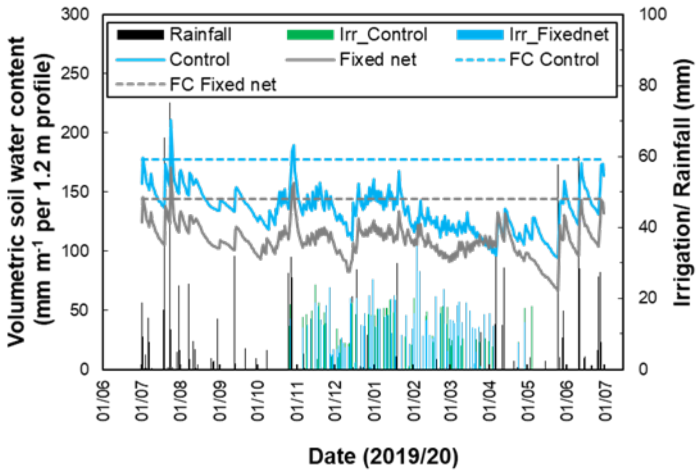


Figure 59 Soil water content (midnight) dynamics, rainfall and irrigation applied for the 'Rosy Glow' control and fixed net treatments for the period 01/07/2019-30/06/2020 during the 2019-2020 season. The field capacity (FC) values determined from hourly soil water content graph trends are also indicated.

4.3 VEGETATIVE GROWTH

4.3.1 Stem growth

In the first season (2018-2019), it appears that stem growth was faster under the nets, increasing by more than 0.5 mm between 8 and 22 November 2018 (Figure 60). The total stem growth in the open treatment was just under 0.4 mm during this period.

It is probable that the low irrigation in the control treatment may explain this trend, but further investigations are required to confirm this. The maximum daily shrinkage was greater for the control than the shade nets treatment, suggesting that the control trees experienced some water stress. When water supply to the evaporating sites in the leaves is lower than the rate of water uptake, stem shrinkage is greater as more water is extracted from the internal pools to meet the transpiration demand (Steppe et al., 2006). This situation typically occurs either when soil water availability is limiting or due to higher hydraulic resistance in the transpiration stream. The later is unlikely given that the same rootstock-scion combination was used for both treatments. No significant differences were found for shoot length growth during the course of the season for trees in the open and under netting (Figure 61).

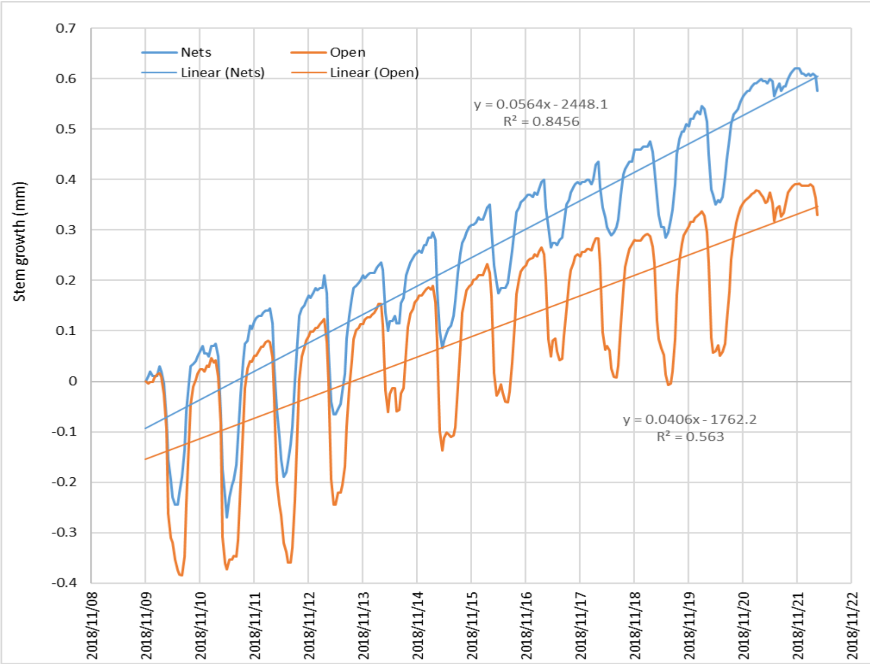


Figure 60. Comparison of stem growth rates under the control and shade net treatments.

4.3.2 Seasonal shoot growth

No significant treatment differences were found for shoot length or relative shoot growth rate in the 2018-2019 season (Figure 61, top figures) and in the 2019-2020 season (Figure 61, bottom figures). In 2018-2019, shoot growth in both treatments was strongly inhibited due to the application of the growth regulator Regalis® (active ingredient prohexadione-calcium), a growth retardant, on 9 and 30 October 2018. This chemical is commonly used for red and blushed apple cultivars in South Africa to control shoot growth and thus create a better light environment for red colour development of fruit. In the trial orchards, a double application was deemed necessary to prevent the excessive growth that was experienced in the previous season (2017-2018) in both treatments but especially under the nets.

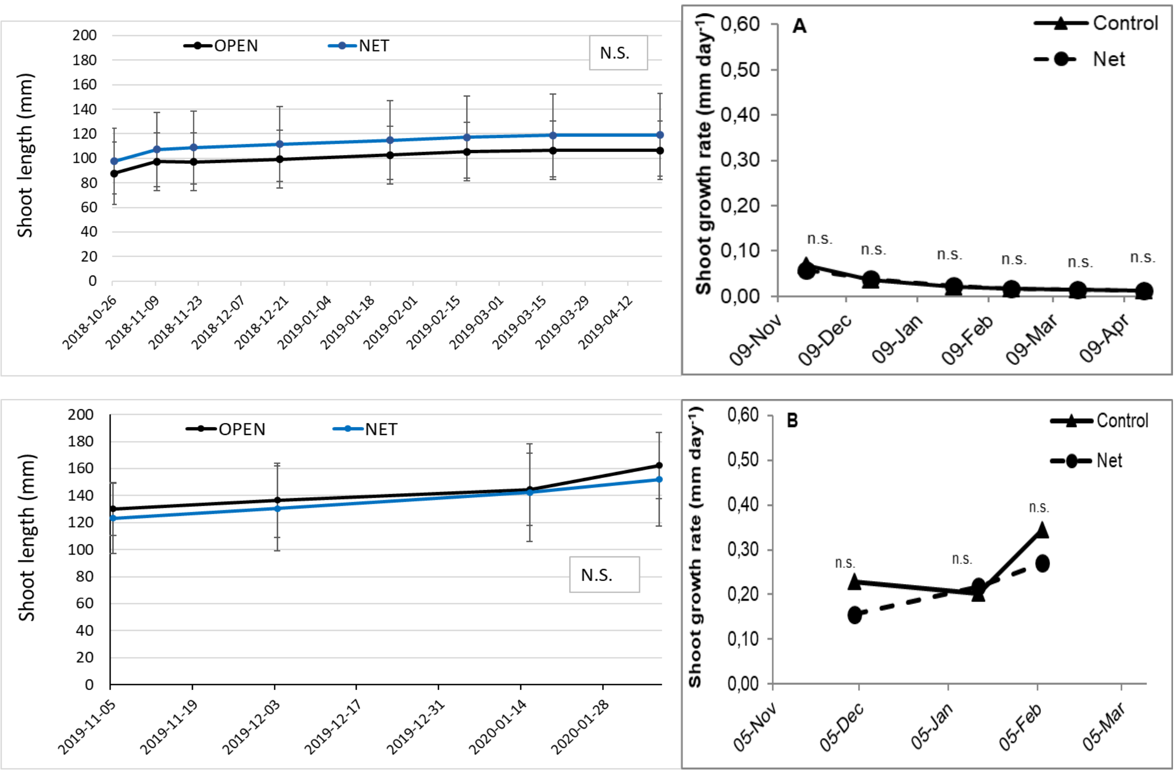


Figure 61. Shoot length and relative shoot growth rate as measured on two tagged shoots per tree (N=20) in the 2018-2019 (top) and 2019-2020 (bottom) seasons. Values for shoot length are means ± standard deviation. N.S. = no significant differences.

4.4 WATER POTENTIAL, GAS EXCHANGE AND WUE

4.4.1 Water potential

Figure 62 shows the diurnal course of changes in Ψ_{leaf} under netting and in the open during the course of the growth season from 28 November 2019 until 23 June 2019. The steep daytime reduction in Ψ_{leaf} is normal for apple trees and the low minimum values do not indicate water stress. Values decreased more rapidly in the morning during the pre-harvest period from December 2018 until March 2019, compared to the post-harvest period (April to June 2019). Lowest minimum values were reached from 1 February until 21 March 2019, the period of highest seasonal ET_o and transpiration. These values were generally reached between 11:00 and 13:00, when daily ET_o and transpiration are at their highest. Only four instances were found where Ψ_{leaf} was significantly different between trees in the open and under netting, although the absolute differences were small. Two of these were found on 28 November (10:00 and 13:00), one at 10:00 on 21 December (not shown), and one at 17:00 on 23 May.

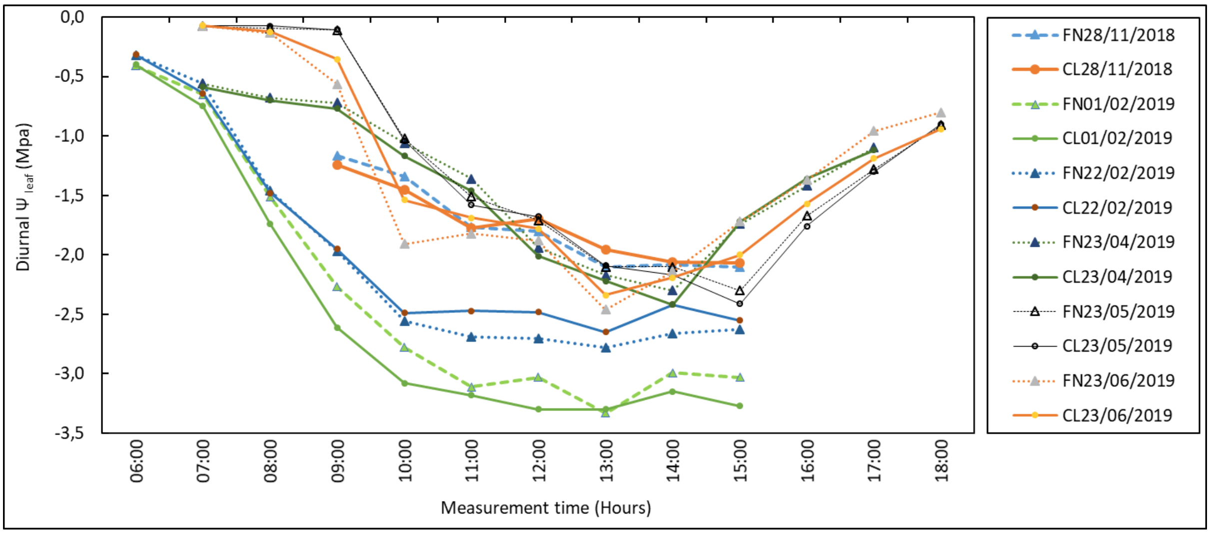


Figure 62 Leaf water potential (unenclosed) from early morning until late afternoon in 2018-2019 as measured on six days through the season from 28 November 2018 until 23 June 2019. Solid lines denote the control treatment and dashed or dotted lines in the same colour denote the net treatment on the same day.

In 2018-2019 (Figure 63a), no significant treatment differences were found through the season for early morning Ψ. In 2019-2020 (Figure 63b), there were again no significant treatment differences until mid-February 2020, when the $\Psi_{pre\text{-}dawn}$ in the control treatment was lower (more negative) than in the netted orchard, although not statistically significant. The treatment difference persisted into March when the trees under netting had a significantly higher $\Psi_{pre\text{-}dawn}$ compared to trees in the open (control treatment).

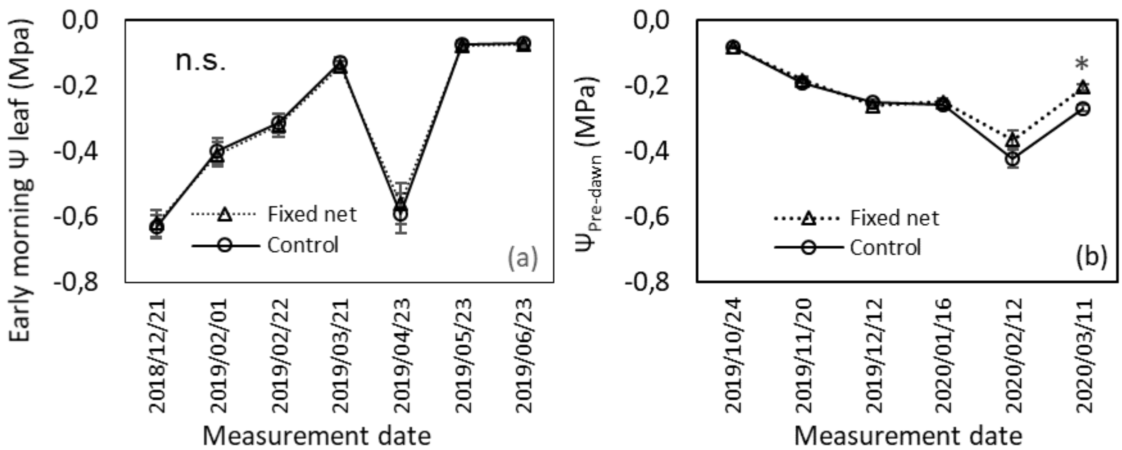


Figure 63 (a) Early morning leaf water potential, 2018-2019, (b) pre-dawn leaf water potential, 2019-2020.

The midday stem water potential (Ψ_{stem}) results (Figure 64) support the conclusion that water stress was unlikely in either treatment on measurement days in the two seasons, since the values were higher than -1.2 MPa which is the widely accepted apple water stress threshold (Naor et al., 1997). An exception was in February of the second season where the open treatment water potential was -1.26 MPa (Figure 64b). The Ψ_{stem} of trees below the net was generally higher compared to the control trees in the mid-summer months January to March when the atmospheric evaporative demand was greatest. The differences were statistically significant in January and March 2019 (Figure 64a) and also in November, February and March 2020 (Figure 64b).

Stem water potential has been widely adopted to determine the water status in fruit trees for better irrigation scheduling (Naor et al., 1997; Chenafi et al., 2016). Considering the midday stem water potential, the current study suggests that both (blocks) orchards experienced no, or only moderate, water stress limitation. The higher midday stem water potential under the net in the warm months was similar to the results by Lopez et al. (2018) using a white net with 20% shading. They reported that 'Imperial Gala' apple trees in the open had Ψ_{stem} values of around -1.0 MPa when they were shaded, but values were lower (up to -1.3 MPa) when they were grown without net. Although the treatment differences in the current study were small, the results suggest that the conditions under the net were more favourable in some periods compared to the control. The differences in both seasons occurred primarily in mid-summer, when solar radiation and ET_o were high. The reduction in radiation and ET_o under the net resulted in improved midday stem water potential through a small but consistent reduction in transpiration, as explained in studies by Conceição and Marin (2009) and Manja and Aoun (2019). This mechanism is well reported for apple trees (Cohen et al., 1997; Cohen and Naor, 2002; Gindaba and Wand, 2007a; Solomakhin and Blanke, 2007, 2008; Kalcsits et al., 2017).

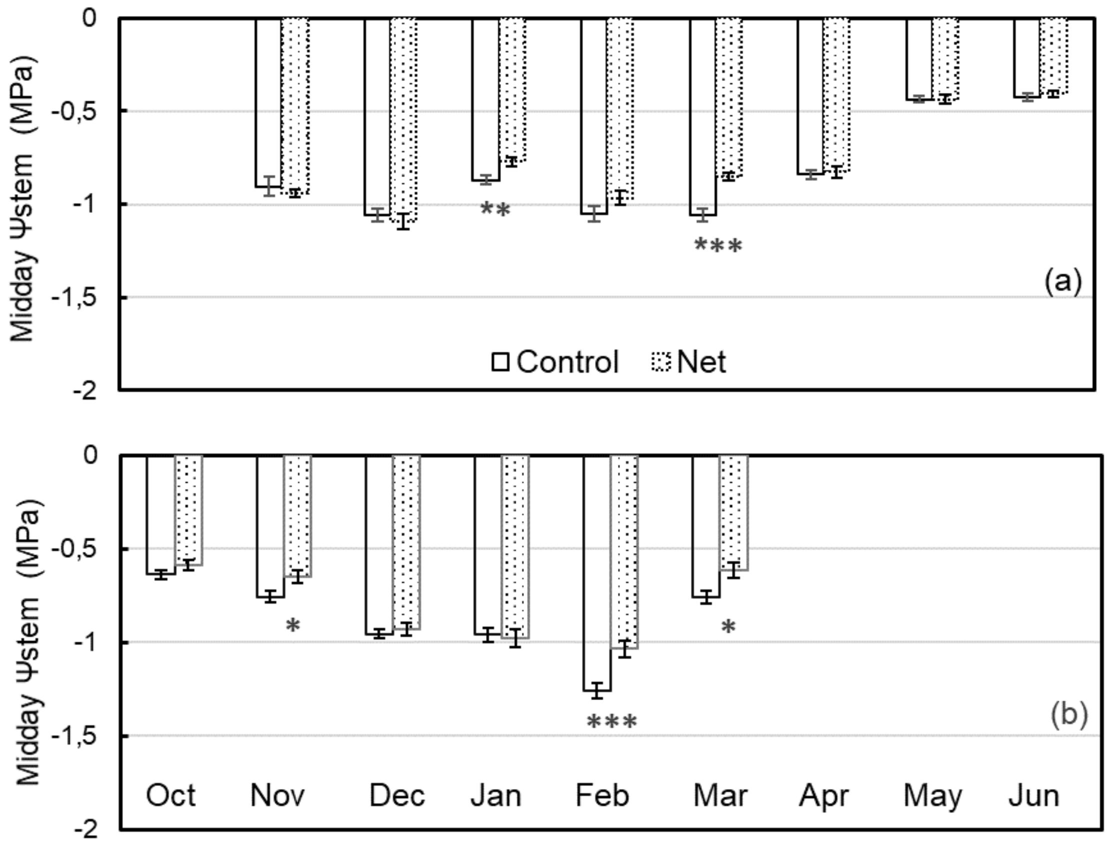


*Figure 64 Midday stem water potential (Ψ_{stem}) of 'Rosy Glow' apple trees during the (a) 2018-2019 and (b) 2019-2020 growing seasons from November or October to June or March, respectively. Values are means ± standard error, and * = P<0.05, ** = P<0.01, *** = P<0.001 according to a T-test.*

4.4.2 Leaf gas exchange and WUE

In both seasons, mean stomatal conductance (g_s) gradually increased from November to January before decreasing in February and either increasing again in March (2019, Figure 65c) or remaining constant (2020, Figure 65d), with the crop still on the trees. After the harvest in 2019, g_s declined rapidly (Figure 65c). Maximum values in 2020 were not as high as those measured in 2019. In 2018-2019, the only significant treatment difference was found in May with netted trees showing slightly higher g_s values than control trees (Figure 65c). In the following season (Figure 65d), g_s was significantly higher in the open (control) than under the net from November until February, but not thereafter.

Net CO_2 assimilation rate (A) generally followed a similar pattern to g_s (Figure 65a and Figure 65b), as did leaf transpiration rate (E) (Figure 65e and Figure 65f). However, no significant treatment differences were found for E in 2018-2019, whereas E was lower under the net from November 2019 to February 2020.

The different results in 2019-2020 are likely due to the changed measurement protocol in this season. Instead of using a constant saturating PPFD inside the cuvette (2018-2019), the PAR in the leaf chamber was set to track the ambient PPFD experienced during the course of the morning in the open or under the net.

WUE_{inst} started higher in the early season, decreased gradually to a minimum in December-March (2018-2019) or December-February (2019-2020), and thereafter increased again (Figure 65g and Figure 65h). Apart from the values for May 2019 and November 2019, when WUE_{inst} values were higher under the net, no other dates showed significant treatment differences.

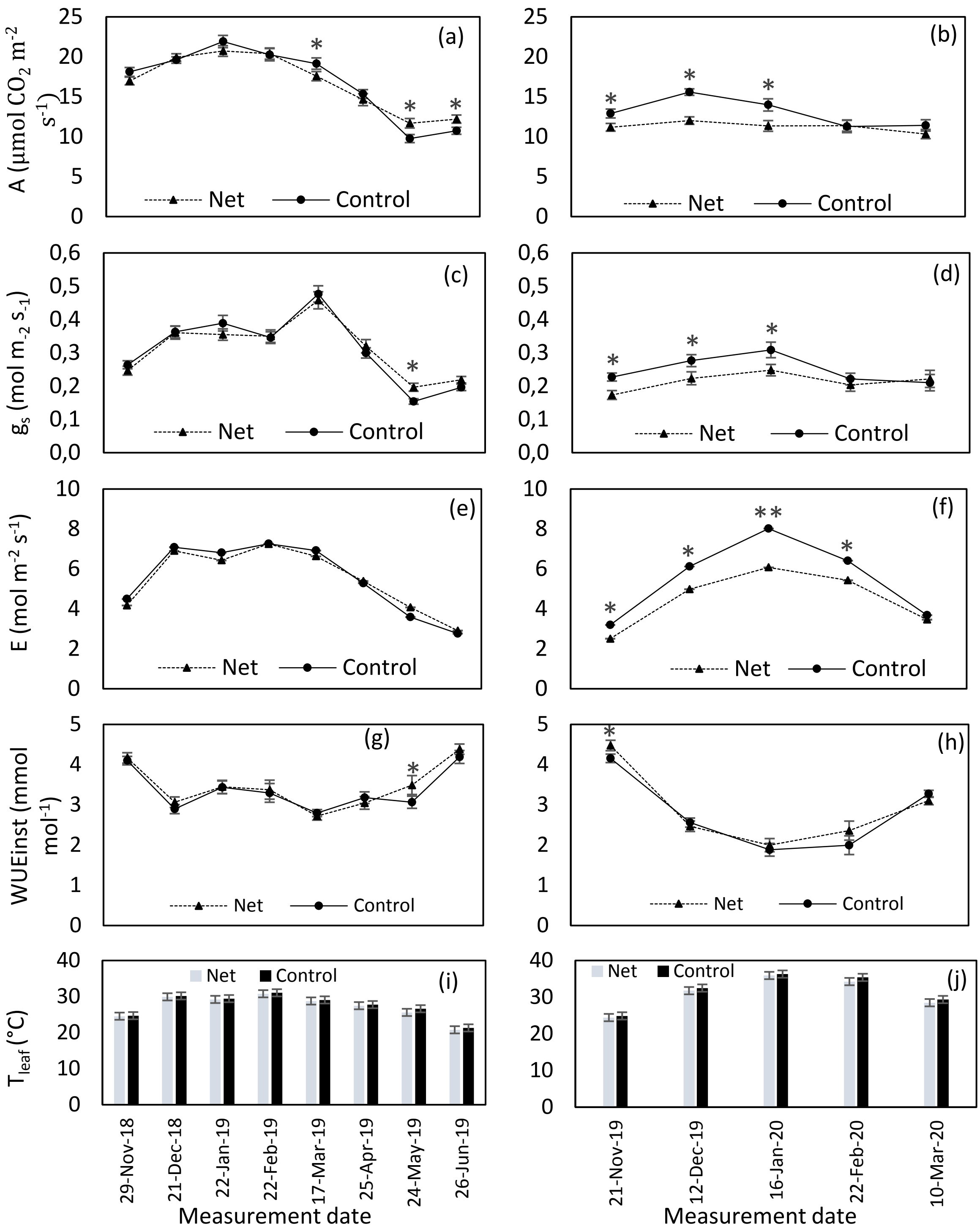


Figure 65 Monthly gas exchange responses of 'Rosy Glow' apples leaves to fixed net compared to open (control) treatments, including (a) and (b): net CO_2 assimilation rate (A); (c) and (d): stomatal conductance (g_s); (e) and (f): transpiration rate (E); (g) and (i): instantaneous water use efficiency (WUE_{inst}); and (i) and (j): leaf surface temperature (T_{leaf}). The left column of figures is for 2018-2019, and the right column is for 2019-2020. Values are means with standard error bars. Means were separated by LSD at 5% when P≤0.05, according to repeated measures ANOVA.

4.5 TREE TRANSPIRATION DYNAMICS AND EVAPORATION

4.5.1 Tree transpiration

Consistent with the weather variables, the fixed nets had a clear effect on the transpiration dynamics of the ‘Rosy Glow’ apple trees (Figure 66). It appears the average transpiration rates of the trees under nets were around 14% less than for control trees. The maximum average transpiration under nets was around 16.7 litres per tree per day compared to 15.9 litres per tree per day under the nets. In equivalent depth units, the maximum transpiration in February was about 3.8 mm/d compared to 3.3 mm/d under the fixed nets (Figure 67).

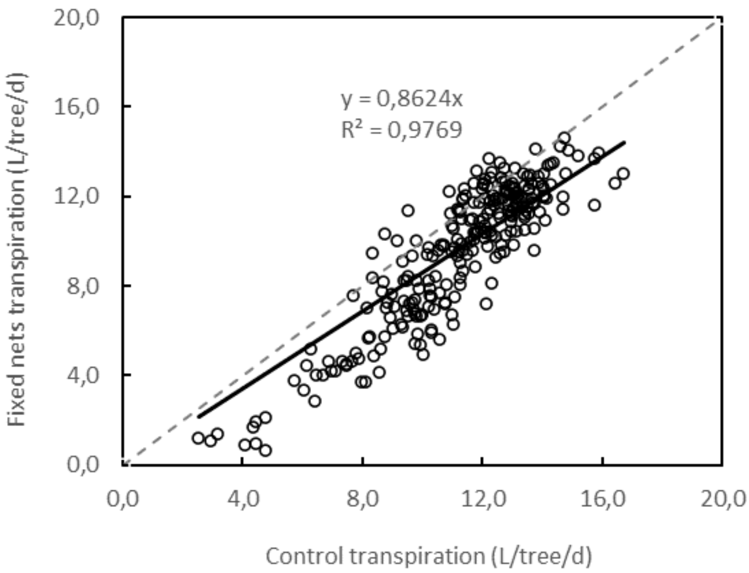


Figure 66 Effect of fixed nets relative to the open (control) treatment on the daily average transpiration volumes (in litres per tree) of ‘Rosy Glow’ apple trees during the 2019-2020 growing season. The dotted line depicts the 1:1 line.

The data in Figure 67 shows that the transpiration differences were largest at the beginning and end of the growing season, and smallest during the summer months, consistent with the observed microclimatic trends presented in Section 4.1.

Trees under both the fixed nets and in the open responded in a similar way to changes in the atmospheric evaporative demand (Figure 68). There was a curvilinear relationship for both treatments and this is consistent with observations on other apple cultivars growing in the open (e.g. Ntshidi et al., 2018; Mobe et al., 2020). What is clear however, in Figure 68 is that the curves for the two treatments diverge at low ET_o levels and appear to converge at high values confirming, that the trees under the two treatments behave in a similar way under high water use rates. The high water use rates coincide with the summer season when irradiance and VPD levels are high.

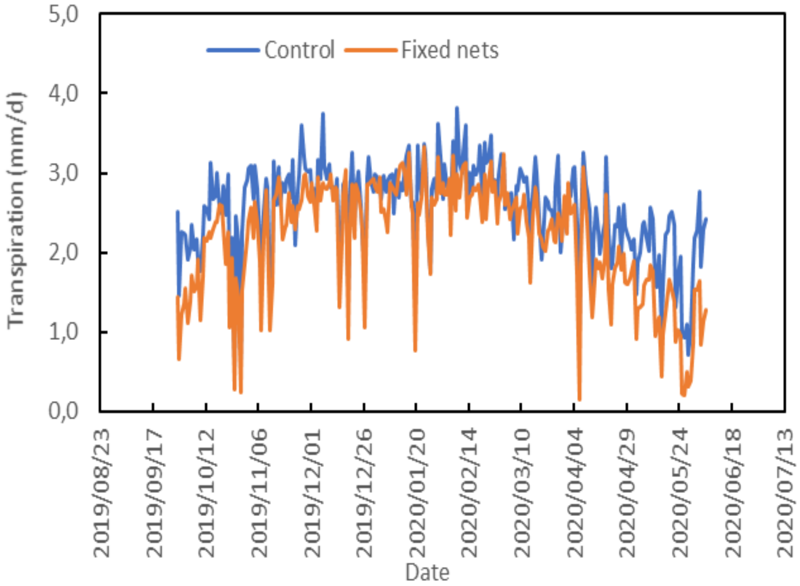


Figure 67 Comparison of the equivalent transpiration depths for 'Rosy Glow' apple trees in the open and under fixed net during the 2019-2020 growing season.

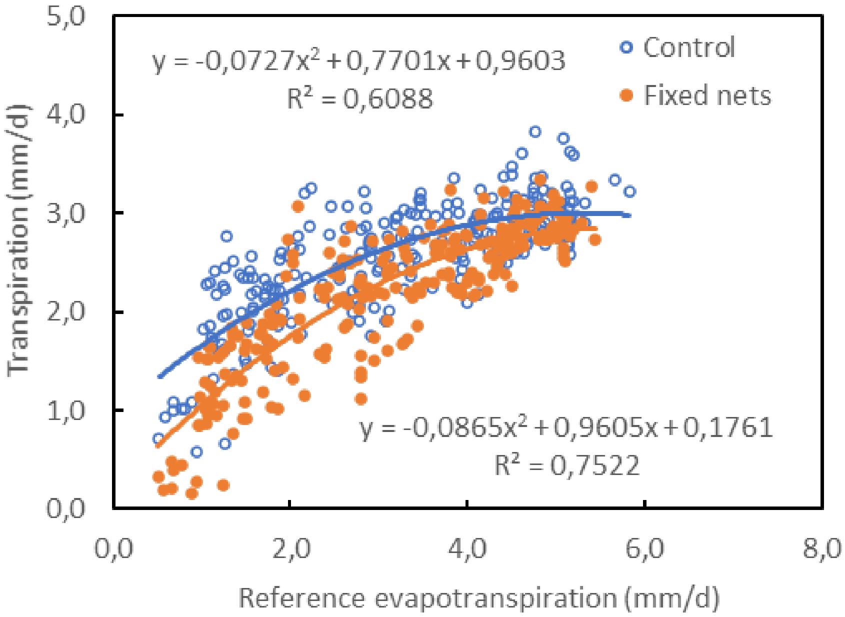


Figure 68 Daily transpiration response of 'Rosy Glow' apple trees under fixed net (orange dots) and in the open (blue dots) to the reference evapotranspiration during the 2019-2020 growing season.

The significance of this result is that the water saving benefits from the shade nets are smaller during the hot dry summer periods and we are uncertain about the cause of this. This could be a result of the small size of the fixed nets which results in mixing of the air between the treatments during unstable conditions in summer. This would be facilitated by the open sides of the nets which allow exchange of air between the treatments.

Table 11 summarizes the monthly transpiration differences for trees in the open and under the fixed nets from October 2019 to May 2020 expressed in cubic meters per hectare. During the irrigation season (October to April), the maximum potential savings in transpiration losses for the 'Rosy Glow' apple orchard was up to 165 m^3/ha, achieved in October 2019. In the period December to March, differences in transpiration between the treatments were less than 10% for the reasons already stated above. Thus, the water saving benefits from the fixed white shade nets appear to be derived outside the period when it is most needed, i.e. in the summer. Clearly, shade netting that has a maximum effect during the warm summer period would be more beneficial from a water saving perspective. At the seasonal time scale, total transpiration by the trees in the open was around 6 250 m^3/ha compared to about 5 360 m^3/ha under the net (Table 11). This represents a difference of around 890 m^3/ha which is about 15% less water use than under the control. However, most of the water savings are derived outside the summer season.

Table 11 Comparison of the total monthly and seasonal transpiration for 'Rosy Glow' trees in the open and under fixed net during the 2019-2020 growing season.

	Open	**Fixed Net**	**Difference**	**Difference**
	(m^3/ha)	(m^3/ha)	(m^3/ha)	(%)
October	711	546	165	23
November	828	721	107	13
December	853	791	62	7
January	881	827	54	6
February	883	803	80	9
March	815	748	68	8
April	712	571	141	20
May	568	358	210	37
Total/Avg	**6251**	**5364**	**887**	**15**

The cumulative differences in the ET_o and transpiration in the open and under fixed net are shown in Figure 69, while Figure 70 shows the effects of irrigation levels on the transpiration. The seasonal total reference evapotranspiration was 877 mm in the open and 797 mm under the fixed net. This represents a 9.5% difference, compared to the 15% difference in transpiration. The seasonal irrigation data presented in Figure 70 carries significant uncertainties. According to these data, more irrigation was applied under the fixed nets at 1 057 mm (or 10 570 m^3/ha) compared to 897 mm (or 8 970 m^3/ha) in the control as reported in Section 4.2.

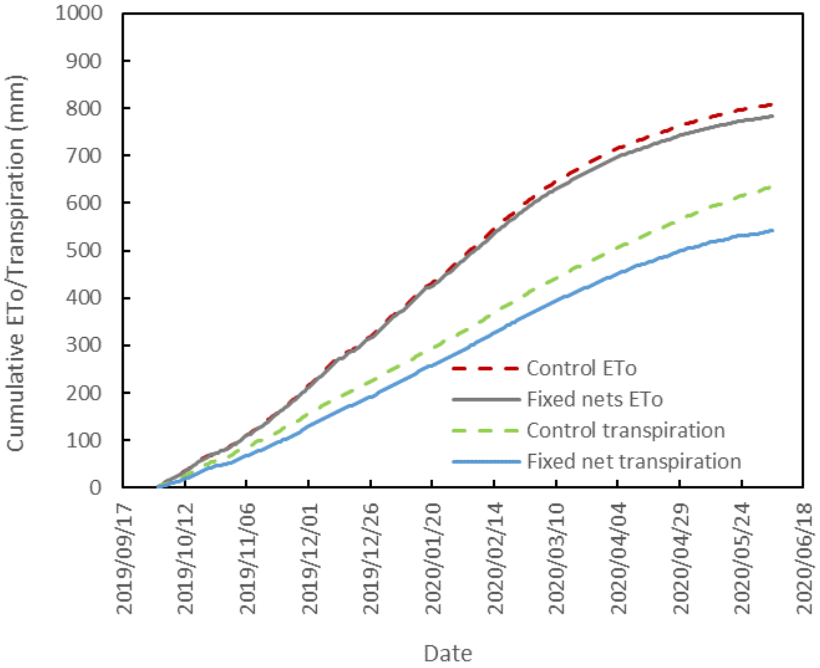


Figure 69 Cumulative reference evapotranspiration and transpiration of 'Rosy Glow' apple trees under the control (dotted lines) and fixed net (continuous lines) treatments during the 2019-2020 growing season.

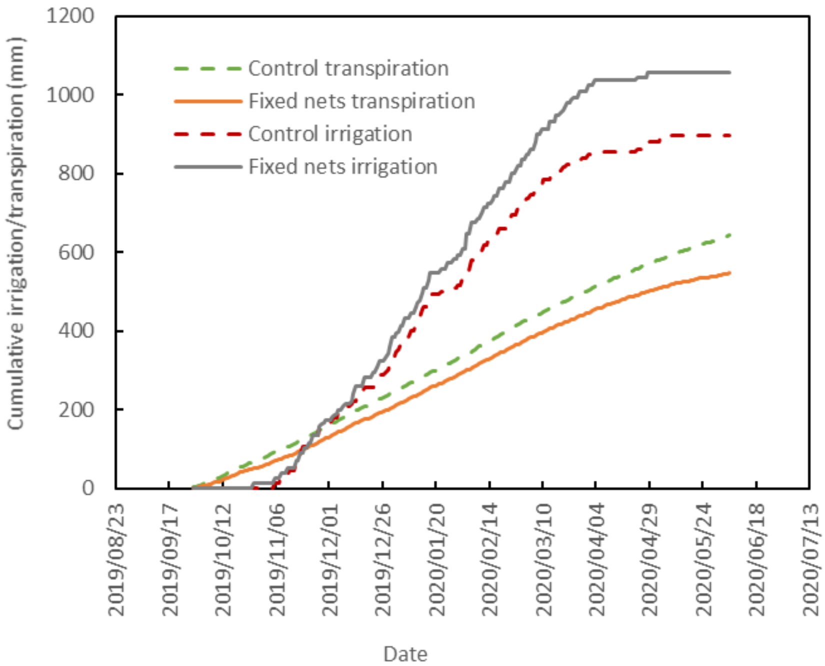


Figure 70 Cumulative irrigation and transpiration of 'Rosy Glow' apple trees under the control (dotted lines) and fixed net (continuous lines) treatments during the 2019-2020 growing season.

4.5.2 Evaporation

Soil evaporation was measured using six microlysimeters under the nets and in the control treatment. The microlysimeters were installed in similar locations under the two treatments to avoid bias. Some were in wetted areas under the trees, others in the open and others in intermediate locations. Hourly data were collected over a period of four days from 28 to 31 January 2020 and typical results are shown in Figure 71. Overall, the evaporation was higher in the control than under the nets.

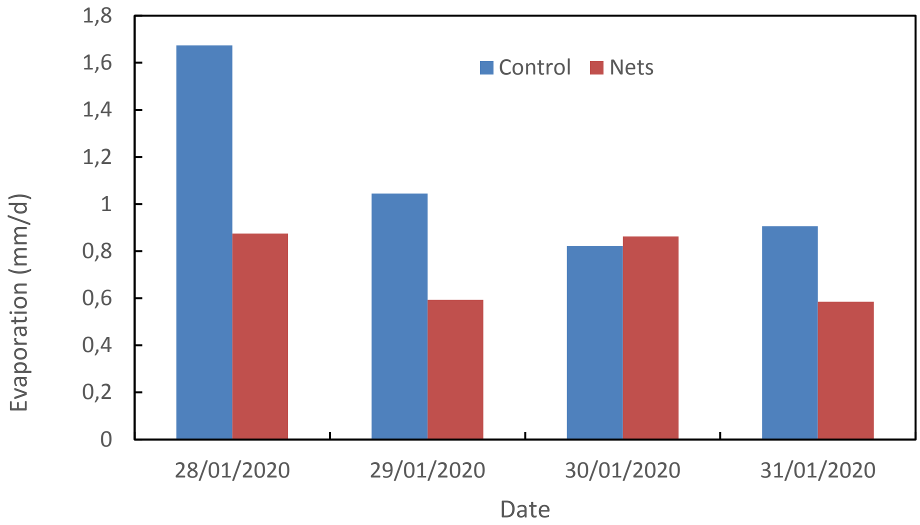


Figure 71 Soil evaporation dynamics in the open and under the fixed nets at Paardekloof.

4.6 ORCHARD EVAPOTRANSPIRATION AND WATER SAVING

4.6.1 Evapotranspiration

The monthly averaged Penman-Monteith reference evapotranspiration (ET_o) and crop evapotranspiration (ET) for the 2019-2020 season are summarized in Figure 72. Monthly averaged ET_o increased from 0.8 mm d^{-1} in July 2019 to 4.7 mm d^{-1} in November 2019, flattening off and reaching a maximum of 5.1 mm d^{-1} in February 2020, after which it decreased gradually to 1.5 mm d^{-1} in June 2020. The ET in general followed the ET_o trend over the season, increasing from c. 0.9 mm d^{-1} in July to a maximum in January/February, after which it decreased gradually from c. 3.6 (±1) mm d^{-1} in March to 1.8 (±1.2) and 1.2 (±0.6) mm d^{-1} in June for the control and fixed net treatments, respectively. The fixed net ET reached a maximum of 4.9±1.7 mm d^{-1} in January, whereas for the control ET (4.7±1.7 mm d^{-1}), peaked in February, consistent with the ET_o trend.

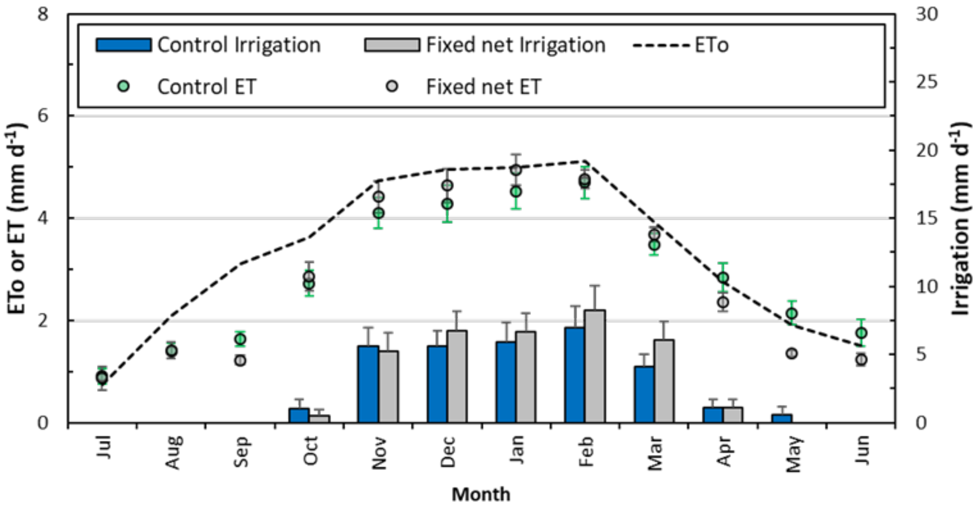


Figure 72 Monthly averaged Penman-Monteith reference evapotranspiration (ET_o), 'Rosy Glow' orchard evapotranspiration (ET) and irrigation applied in the open (Control) and below fixed net at Paardekloof. Error bars indicate the standard error.

Based on monthly averaged values, the control treatment ET in general was comparable to or slightly lower than ET below fixed net throughout the season until March (Figure 72). The exception was September during which ET of the control treatment was higher than the ET below fixed net. During November, December and January the ET below the fixed net increased over time and was 7.8, 8.3 and 8.9%, respectively, higher compared to control treatment ET. From April until June the trend changed and control treatment ET tended to be or was higher compared to the ET below fixed net. The monthly total ET for the control was 17%, 37% and 26% more than ET below fixed net during April, May and June, respectively (Table 12).

Monthly averaged amounts of irrigation applied per day (±standard error) did not differ between treatments except for May, during which the fixed net orchard did not receive any irrigation. However, based on the seasonal total amounts (Table 12), the fixed net orchard received 12% more irrigation than the control (i.e. 10 443 m^3 ha^{-1} for fixed net compared to 9 359 m^3 ha^{-1} for the control). The seasonal total ET from 1 July 2019 until 30 June 2020 for the fixed net orchard amounted to 9 845 m^3 ha^{-1} compared to 9 919 m^3 ha^{-1} for the control (Table 13). The total ET from full bloom in 2019 until 30 June 2020 did not differ between the two treatments in real terms and amounted to 9 033 m^3 ha^{-1}. The ET from 1 July until full bloom for the control and fixed net treatment comprised 8.9% and 8.3% of the seasonal ET.

Table 12 Comparison of the total monthly and seasonal evapotranspiration for 'Rosy Glow' trees in the open and under fixed net during the 2019-2020 growing season. Data for October until May are for comparison with transpiration data.

Month	**Evapotranspiration**			
	Control (m^3 ha^{-1})	**Fixed net** (m^3 ha^{-1})	**Difference** (m^3 ha^{-1})	**Difference** %
July	100	104	-4	-4
August	379	408	-29	-8
Sep	475	355	120	25
Oct	817	858	-40	-5
Nov	1228	1324	-95	-8
Dec	1328	1437	-110	-8
Jan	1405	1530	-126	-9
Feb	1362	1381	-19	-1
Mar	1080	1140	-60	-6
Apr	825	684	141	17
May	536	339	197	37
Jun	385	285	100	26
Oct-May	8580	8692	-112	-1
Jul-June	9919	9845	75	1
Full Bloom-June	9033	9032	1	0.01

Table 13 Comparison of the total monthly and seasonal irrigation for 'Rosy Glow' trees in the open and under fixed net during the 2019-2020 growing season.

Month	**Irrigation**			
	Control ($m^3\ ha^{-1}$)	**Fixed net ($m^3\ ha^{-1}$)**	**Difference ($m^3\ ha^{-1}$)**	**Difference %**
Oct	305	143	162	53
Nov	1675	1569	106	6
Dec	1728	2094	-365	-21
Jan	1842	2053	-211	-11
Feb	2028	2380	-352	-17
Mar	1282	1874	-591	-46
Apr	318	331	-13	-4
May	179	0	179	100
Jun	0	0	0	
Oct-May	**9359**	**10443**	**-1085**	**-12**

In summary, 'Rosy Glow' evapotranspiration from November 2019 until January 2020 was about 8.3% higher below the fixed net than for the control treatment (open), whereas control ET exceeded that below fixed net for the months April until June by 25% on average. For the 2019-2020 season there was for 'Rosy Glow' no real difference in the seasonal ET from July 2019 until June 2020 outside or below the fixed net and the seasonal ET – from full bloom 2019 until end June 2020 – amounted to 9033 $m^3\ ha^{-1}$. It should be noted that trees received limited irrigation during April and May which may have affected ET late in the season.

4.6.2 Water saving

When the provisional calculations are made for the full year (July to June) a small ET-based water saving of 74 $m^3\ ha^{-1}$ is found under the nets compared to the open (Table 14). However, during the fruit season (October to June, trees in leaf) there was a very small increase in ET under the nets. This value (12 $m^3\ ha^{-1}$) falls well within the margin of error for measurements and modelling, and the results do not justify a clear statement of change in water use between the two treatments.

When expressed as $m^3\ ton^{-1}$ (ET-based water use efficiency), both the annual and seasonal values do not significantly differ between the two treatments. This is due to the small differences in ET and yield between the treatments.

Our current values indicate an annual increase in irrigation under the nets of 1084 $m^3\ ha^{-1}$ compared to the open treatment. The farm management indicated that irrigation was increased in response to perceived stronger tree activity and growth under the nets. Sufficient data on growth and changes in LAI is not available to interrogate this.

Lastly, we estimated the irrigation productivity using both the irrigation and yield data. The values indicate a higher irrigation water use for every ton of fruit produced under the nets (by 12 m^3 ton^{-1}).

Table 14. Total evapotranspiration (ET, m^3 ha^{-1}), water use efficiency based on ET (WP, m^3 ton^{-1}), irrigation applied (m^3 ha^{-1}), and irrigation productivity (IP, m^3 ton^{-1}) for 'Rosy Glow' trees in the open and under fixed nets during the 2019-2020 growing season, and the difference (potential water "saving" – if positive; potential water "over-spending" – if negative). Values are shown for the full year (July to June) and for the fruit season when trees are in leaf (October to June).

	ET Control	**ET Fixed Nets**	**Difference (Control – Nets)**
July to June (m^3 ha^{-1})	9919	9845	74
October to June (m^3 ha^{-1})	8966	8978	-12
	WUE Control	**WUE Nets**	**Difference (Control – Nets)**
July to June (m^3 ton^{-1})	87.4	89.0	-1.6
October to June (m^3 ton^{-1})	79.0	79.1	-0.1
	Irrigation Control	**Irrigation Nets**	**Difference (Control – Nets)**
July to June (m^3 ha^{-1})	9359	10443	-1084
	IP Control	**IP Nets**	**Difference (Control – Nets)**
July to June (m^3 ton^{-1})	82	94	-12

4.7 YIELD, FRUIT MATURITY AND FRUIT QUALITY

4.7.1 Fruit growth

In 2018-2019, at the first measurement date (31 days after full bloom (DAFB)), the netted fruit (23.8 mm) were larger than the control (22.4 mm) (P=0.0039). At the final date (160 DAFB) the netted fruit (77.5 mm) remained significantly larger than the control (69.7 mm) (P=0.0002). In 2019-2020, fruit from both treatments ca. 24.4 mm at 39 DAFB (P=0.8678). At the final date (132 DAFB), the netted fruit (65.1 mm) were significantly larger than the control fruit (60.5 mm) (P=0.0006). The relative fruit growth rate of the netted fruit was significantly higher on every measurement date in both seasons (Figure 73).

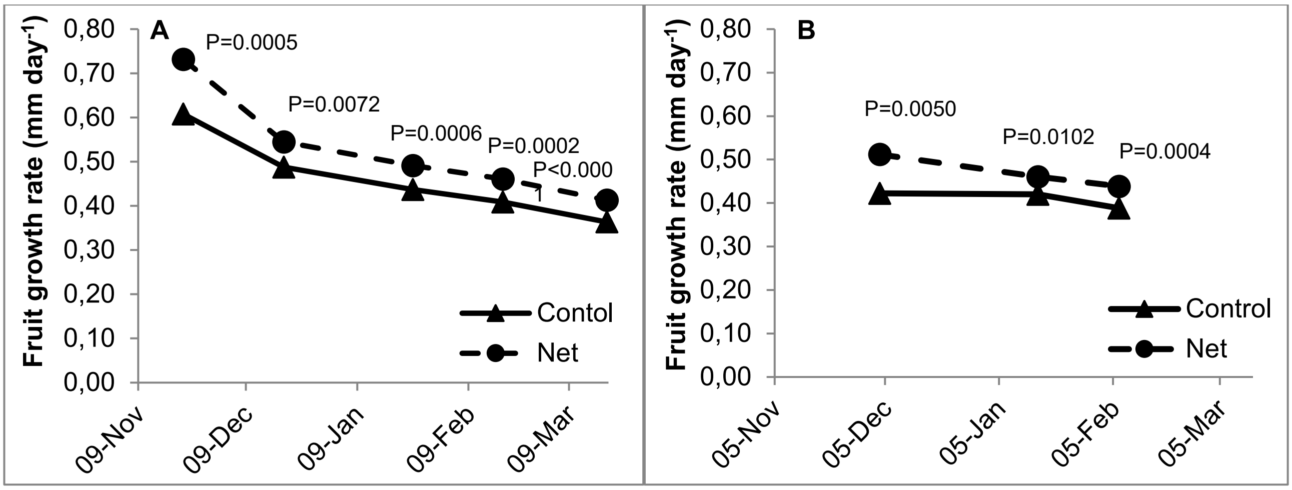


Figure 73 Fruit relative growth rate under net and in the open of A) 'Rosy Glow' (2018-2019), B) 'Rosy Glow' (2019-2020)

4.7.2 Yield, fruit maturity and fruit quality

During the 2018-2019 season, for the ten trial trees per treatment, yield and the number of fruit picked during the first pick (H1) were higher in the control compared to the net treatment (Table 15). There were no significant differences for the second pick (H2), but yield and fruit number were significantly higher in the control when the combined harvest data was analysed. The yield efficiency for the full harvest was also higher in the control. Yield in the open ranged between 105 and 176 t ha^{-1} with a median value of 136 t ha^{-1}. Under netting it ranged between 62 and 147 t ha^{-1} with a median value of 105 t ha^{-1}. Data provided by the farm showed that the yield of the whole open orchard was 132 t ha^{-1} while the yield for the whole orchard under white netting was 139 t ha^{-1} (in 2018 the values were 118 t ha^{-1} for both orchards). Thus, the ten trial trees in the open were representative of the whole orchard. However, the ten trial trees under netting had a lower yield than the whole orchard.

The mean yield in both treatments was high by South African standards. Increasingly, apple growers are achieving yield of >100 t ha^{-1}, but the whole orchard yields achieved in this trial were exceptionally high (compare generally lower yields reported in Dzikiti et al., 2018a). This was attributed by the farm manager to strong flowering and fruit set and a mild season climatically.

For both harvest 1 and harvest 2, sampled fruit were significantly larger and heavier under netting compared to the open (Table 15). Samples drawn by the farm for quality control purposes gave a mean fruit mass of 171 g for the open orchard, and 183 g for the netted orchard. These values fall within one standard deviation of our sample means. The average individual fruit mass over the previous four years (2015-2018) was 158 g for both orchards. The fruit harvested in 2019 were thus exceptionally large. The analysis of fruit size distribution (Figure 74A) shows that a higher percentage of fruit has sufficient size for carton counts 100 and lower (fruit diameter ≥79 mm). Depending on the target market, these counts usually fetch a higher price.

The lower crop load on netted trees influenced the larger mean fruit mass in that treatment (Table 15, Figure 74A). The smaller fruit mass in the open was related to the higher crop load on those trees, at least in the first season. It is not known why the crop load was higher under the netting, since the canopy sizes were kept similar through management practices. A similar fruit thinning programme was employed in both orchards and the standard crop load estimates suggested that, at least initially, the target crop load was achieved in both. It is possible that there was a higher rate of fruit abscission following initial fruit set in the open, possibly due to strong wind in that period. Another possibility is that the early summer pruning removed a greater proportion of fruit from trees under the netting, but this is deemed unlikely. However, fruit diameter and mass differences between treatments persisted in the second season even though the yields did not differ between treatments. Fruit numbers were not counted in this season, so it is not possible to speculate on the reasons.

Table 15 Yield, fruit number per tree, yield efficiency, fruit diameter, and individual fruit mass for the net and control treatments. Means followed by the same lowercase letter were not significantly different at the 5% level according to Fisher's LSD test.

Treatment	Yield (t ha^{-1})	Fruit number	Yield efficiency (kg cm^{-2} TCA)	Fruit diameter (mm)	Fruit mass (g)
'Rosy Glow' (2019) H1*					
Net	50.3 b	119 b		78.1 a	204.3 a
Control	74.5 a	211 a		72.2 b	167.1 b
P-value	0.0003	<0.0001		<0.0001	<0.0001
'Rosy Glow' (2019) H2*					
Net	54.4 ns	126 ns		77.7 a	199.5 a
Control	61.8	181		71.3 b	159.2 b
P-value	0.4456	0.1123		<0.0001	<0.0001
'Rosy Glow' (2019) All fruit					
Net	104.7 b	246 b	0.13 b	77.9 a	187.9 a
Control	136.3 a	393 a	0.19 a	71.8 b	153.0 b
P-value	0.0038	0.0004	0.0007	<0.0001	<0.0001
'Rosy Glow' (2020)					
Net	103.0ns	-	0.20 ns	78.8 a	206.4 a
Control	107.2	-	0.22	76.1 b	188.4 b
P-value	0.7668	-	0.6526	0.0006	0.0013

*First harvest = H1 and second harvest = H2

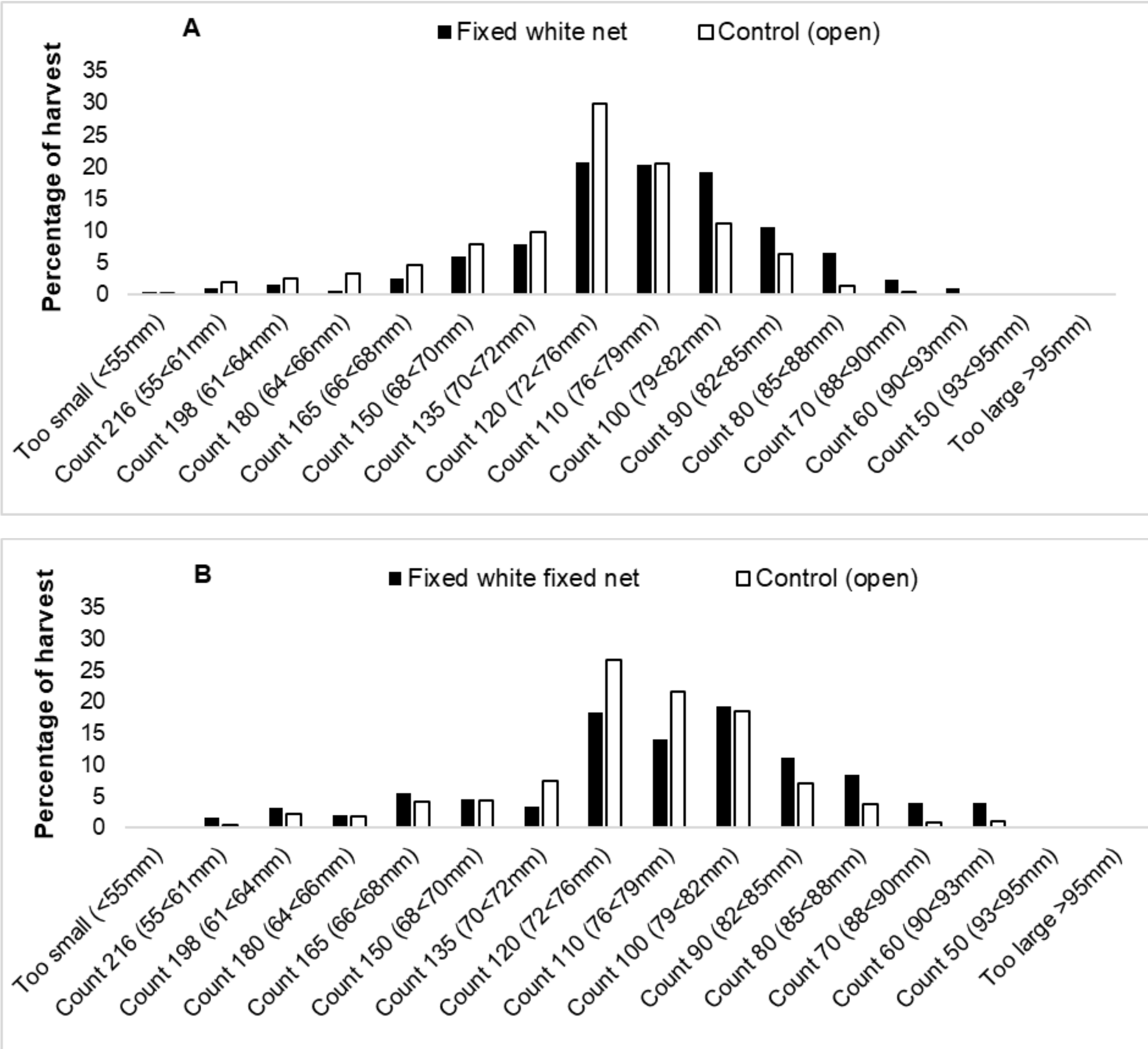


Figure 74 Fruit size distribution of the full harvest of 'Rosy Glow' under fixed white net in (A) 2018-2019 and (B) 2019-2020. Data was provided by the pack house.

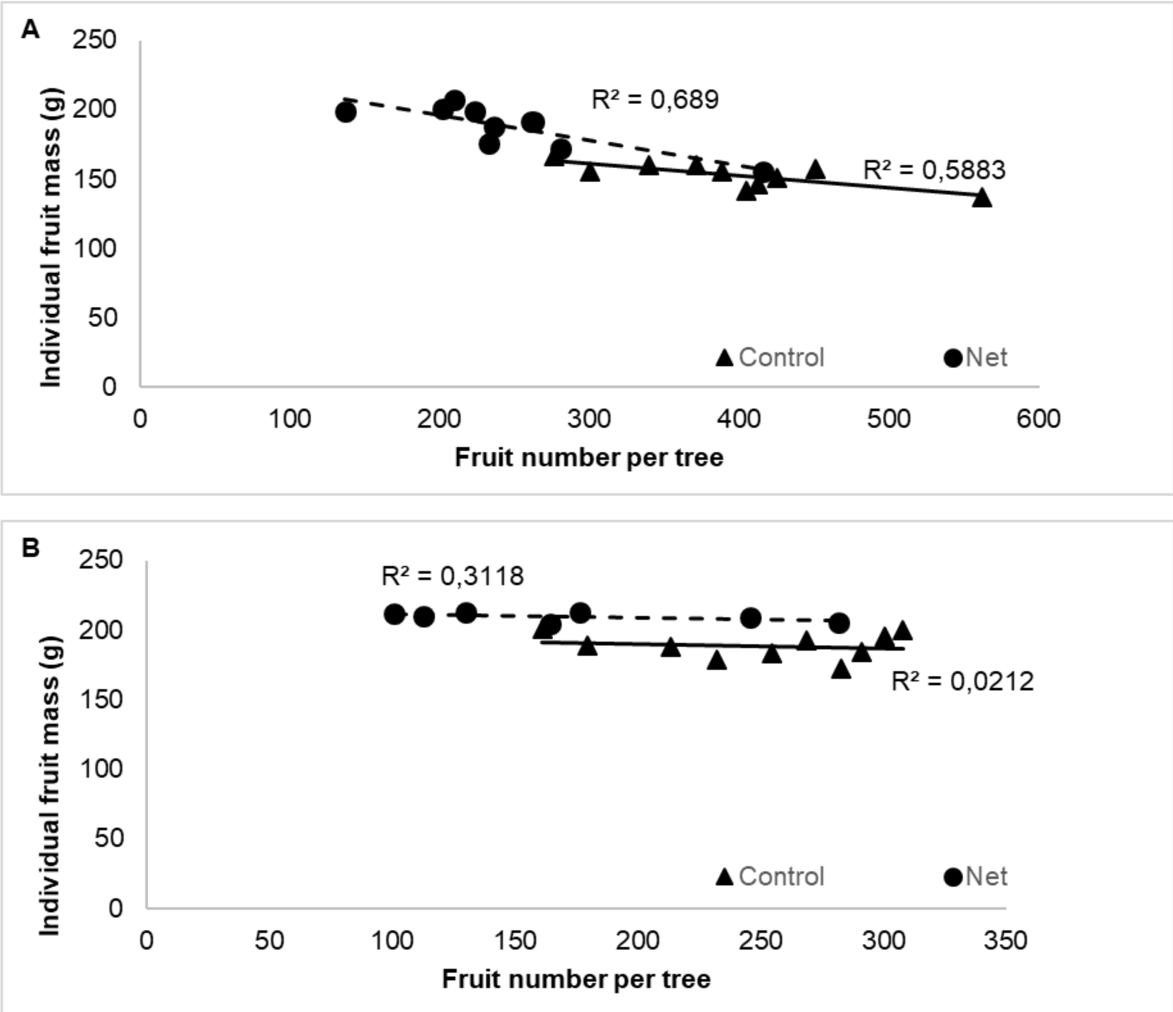


Figure 75. Relationships between mean individual fruit mass and fruit number per tree for the two treatments in (A) 2018-2019 and (B) 2019-2020.

During the 2019-2020 season, no treatment differences were found for yield or yield efficiency (Table 15). The mean yield for the netted (103 t/ha) and open (107 t/ha) trees was similar, and close to the farm yield data (Table 16) of 111 and 114 t/ha, respectively. Fruit from trees under netting were larger and heavier compared to the control (Table 15), a result also reported by the pack house (Table 16). The fruit size distribution (Figure 74B) shows that, while there was a slightly higher frequency of smaller fruit under the net (up to count 150), there were relatively fewer apples in the medium count range (135, 120 and 110) under the net compared to the control. From count 100 upwards (fruit size >79 mm) the percentage of fruit was clearly higher in the net treatment. The relationship between fruit number and average fruit mass showed a consistently higher mass under netting across all crop loads (Figure 75B).

Table 16 Pack house data for yield, individual fruit mass, other key fruit quality criteria, and packout percentage for the different class grades for 'Rosy Glow' apples grown under white fixed netting, compared to the open (control).

Variable	Net	Control
'Rosy Glow' (2019)		
Yield (t ha^{-1})	139	132
Individual fruit mass (g)	183	171
Poor red colour (%) (<40% red colour)	50	30
Sunburn (%)	1.1	5.0
Hail damage (%)	0.9	3.9
Class 1 PLD (Pink Lady®)	29	20
Class 2 CCP ('Cripps Pink')	51	36
Class Super	0	3
Class 3	20	41
'Rosy Glow' (2020)		
Yield (t ha^{-1})	111	114
Individual fruit mass (g)	184	170
Poor red colour (%) (<40% red colour)	35	18
Sunburn (%)	1.1	5.0
Hail damage (%)	0.7	6.9
Class 1 PLD (Pink Lady®)	52	55
Class 2 CCP ('Cripps Pink')	40	35
Class 3	8	10

Fruit quality and maturity under the two treatments are presented in Table 17, Table 18 and Table 19. Red peel colour (% cover) was slightly reduced at first pick in 2019 but this was not seen in the second pick (Table 17). Data for red colour could not be obtained in 2020. However, background colour was slightly greener in the control treatment in 2020. In both seasons, the number of healthy viable seeds was significantly reduced under the netting compared to the control (Table 17). This suggests a reduction in pollination effectiveness under the net.

No significant treatment differences were found for fruit firmness in both seasons (Table 18). Percentage starch breakdown was slightly higher under netting at the first pick of 2019, and TSS was significantly higher under netting in the second pick of 2019. The concentration of malic acid (and other organic acids, results not shown) was higher in the net treatment in 2019.

Sunburn damage was significantly reduced by the netting in both seasons (Table 19). In 2019, no sunburn was seen in fruit from the netting treatment compared to a 12.2% incidence in the control. In 2020, this figure was 14.5%, with the net treatment having 1% of fruit in sunburn class 1 (very slight damage, still marketable).

A summary of significant differences in fruit maturity and quality of ‘Rosy Glow’ apples grown under fixed white netting and in the open at this site is provided in Table 20. The positive impacts on fruit size and mass, sunburn damage and hail damage are likely to be of greatest commercial value. The slightly negative impact on red colour is the only identified drawback of netting on fruit quality. Other significant effects of fixed netting on quality and maturity did not have an impact on the pack out percentage (Table 16) and the commercial value of the crop (see next section).

Table 17 Fruit background colour, red intensity, red colour percentage cover, and the number of viable seeds for the net and control treatments. Means followed by the same lowercase letter were not significantly different at the 5% level according to Fisher’s LSD test.

Treatment	Background colour (chart)	Red intensity (chart)	Red cover (%)	Seed count
		‘Rosy Glow’ (2019) H2*		
Net	3.00 ns	8.08 ns	61.5 b	4.33 b
Control	2.86	7.79	66.4 a	5.81 a
P-value	0.2525	0.3035	0.0048	0.0009
		‘Rosy Glow’ (2019) H2*		
Net	3.20 ns	6.23 ns	46.7 ns	3.95 b
Control	3.21	6.40	50.1	5.17 a
P-value	0.9087	0.7503	0.4878	0.0140
		‘Rosy Glow’ (2020)		
Net	3.29 a	-	-	3.37 b
Control	3.09 b	-	-	4.71 a
P-value	0.0178	-	-	0.0165

*First harvest = H1 and second harvest = H2

Table 18 Fruit firmness of sun and shade exposed sides, percentage starch breakdown, total soluble solids (TSS) concentration and malic acid concentration for the net and control treatments. Means followed by the same lowercase letter were not significantly different at the 5% level according to Fisher’s LSD test.

Treatment	Firmness – sun (kg)	Firmness – shade (kg)	Starch breakdown (%)	TSS (%)	Malic acid (g 100g^{-1})
		‘Rosy Glow’ (2019) H1*			
Net	9.09 ns	-	21.7 a	13.2 ns	0.67 a
Control	9.04	-	16.8 b	13.2	0.60 b
P-value	0.6488	-	0.0364	0.9129	0.0077
		‘Rosy Glow’ (2019) H2*			
Net	8.74 ns	-	53.0 ns	12.9 a	0.64 a
Control	8.67	-	54.0	12.3 b	0.58 b
P-value	0.5088	-	0.3349	0.0199	0.0287
		‘Rosy Glow’ (2020)			
Net	8.21 ns	8.43 ns	42.8 ns	14.0 ns	0.44 ns
Control	8.24	8.45	41.9	13.8	0.42
P-value	0.7412	0.9277	0.7503	0.4562	0.3643

*First harvest = H1 and second harvest = H2

Table 19 Sunburn incidence, sunburn score (according to a colour chart), and the proportion of fruit in each sunburn class for the net and control treatments. C0 = no sunburn, while C1-C3 are categories for increasing severity of sunburn. Means followed by the same lowercase letter were not significantly different at the 5% level according to Fisher's LSD test.

Treatment	**Sunburn incidence (%)**	**Sunburn score (Chart)**	**Sunburn C0 (%)**	**Sunburn C1 (%)**	**Sunburn C2 (%)**	**Sunburn C3 (%)**
			'Rosy Glow' (2019) H1*			
Net	0.0 b	0.0 b	100.0 a	0.0 b	0.0 b	0.0
Control	12.2 a	0.16 a	87.8 b	8.7 a	3.5 a	0.0
P-value	<0.0001	0.0002	<0.0001	<0.0001	0.0511	-
			'Rosy Glow' (2020)			
Net	1.0 b	0.01 b	99.0 a	1.0 b	0.0 b	0.0
Control	14.5 a	0.20 a	85.5 b	9.0 a	5.5 a	0.0
P-value	0.0012	0.0014	0.0012	0.0028	0.0054	-

Table 20 Summary of commercial significance of changes in fruit maturity and quality of 'Rosy Glow' apples sampled from the netted orchard relative to apples sampled from the open orchard, for 2018-2019 and 2019-2020. The likely commercial significance of the changes is indicated. (+) = positive commercial impact; (-) = negative commercial impact. An "-" indicates that values were not statistically significantly different for the sample assessment. "Orchard" indicates a result only for the full harvest.

Parameter	**Commercial significance**	
	2018-2019	**2019-2020**
Yield	Some significance (+) (orchard)	-
Ind. fruit size and mass	High significance (+)	High significance (+)
Ground colour	-	Not significant (-)
Higher % apples red colour (export)		High significance (+)
Higher % apples poor red colour	Some significance (-) (1st pick)	High significance (-)
% Starch breakdown advanced	Not significant (1st pick)	-
TSS – higher	Not significant (+) (2nd pick)	-
Organic acid concentration	Not significant (+)	-
Sunburn – lower	High significance (+)	High significance (+)
Hail damage – lower	High significance (+)	High significance (+)
Viable seed count	Not significant (-)	Not significant (-)

4.8 WATER PRODUCTIVITY

4.8.1 Seasonal transpiration and evapotranspiration

In 2018-2019, treatment differences in the daily maximum transpiration per tree were small, peaking at 20.5 L $tree^{-1}$ day^{-1} in the open compared to 19.8 L $tree^{-1}$ day^{-1} under the net (Table 21). The average daily transpiration per tree for the period 09 November 2018 to 31 May 2019 was 13.2 and 12.1 L $tree^{-1}$ day^{-1} for the control and shade net treatments, respectively.

An average tree under the nets transpired 2 331 litres compared to 2 542 litres in the open (Table 21). Thus, on average, each tree in the open transpired about 210 litres more than under the nets. Tree density in the orchard was about 2285 trees per hectare. Potential water savings as a result of transpiration reduction amounted to more than 480 000 L ha^{-1} which is quite substantial. However, if missing data for the first part of the season were to be included, it is clear that potential transpiration-related water savings would exceed 0.5 million L ha^{-1} per season for the 'Rosy Glow' orchard under fixed white netting at Paardekloof.

Converting the tree sap flow into equivalent depth units, transpiration under nets peaked at 4.5 mm d^{-1} compared to 4.7 mm d^{-1} in the control treatment (Table 21). The average daily transpiration rates were 3.0 and 2.8 mm d^{-1} for the control and netted treatments, respectively. Total transpiration from 09 November 2018 to 31 May 2019 was about 581 mm in the open compared to 533 mm under fixed netting. This amounts to water use rates of about 5 810 and 5 330 m^3 ha^{-1}, respectively, and a transpiration-related water saving of 480 m^3 ha^{-1}.

Despite the control orchard having a very high tree density, compared to the mature ‘Cripps Pink’ orchards studied by Gush and Taylor (2014) and Dzikiti et al. (2018a) in the same production region, the water use rates were quite similar. Gush and Taylor reported a total transpiration of 6 870 m^3 ha^{-1}, but this data was collected over a much longer period spanning the whole year. Dzikiti et al. (2018a) reported a seasonal total transpiration of 5 890 m^3 ha^{-1} for the period October 2014 to May 2015, which is very similar to the water use rates for the control treatment in this study. The total transpiration under the nets was clearly lower than the values for open treatments obtained in the same study area.

Table 21. Daily and total seasonal transpiration in the control and fixed nets treatments at Paardekloof in 2018-2019.

Parameter	Mean T (L day^{-1})		Mean T (mm day^{-1})	
	Open	Netted	Open	Netted
Daily maximum	20.5	19.8	4.7	4.5
Daily average	13.2	12.1	3.0	2.8
Total seasonal	2542 (L $tree^{-1}$)	2331 (L $tree^{-1}$)	580.9 (mm)	532.7 (mm)

Table 22. Daily and total seasonal transpiration and seasonal evapotranspiration in the control and fixed nets treatments at Paardekloof in 2019-2020.

Parameter	Mean T (L day^{-1})		Mean T (mm day^{-1})	
	Open	Fixed Net	Open	Fixed Net
Daily maximum	16.7	15.9	3.8	3.3
Daily average	11.2	9.5	2.6	2.2
Total seasonal	2814 (L $tree^{-1}$)	2390 (L $tree^{-1}$)	642.9 (mm)	546.2 (mm)
Parameter			**Total ET (mm)**	
			Open	**Netted**
Total seasonal			991.9 (mm)	984.5 (mm)

In 2019-2020, the maximum average transpiration of the trees without net (control) was around 16.7 L $tree^{-1}$ day^{-1} compared to 15.9 L $tree^{-1}$ day^{-1} under the net as presented earlier (Table 22). The average daily transpiration per tree for the whole period was 11.2 and 9.5 L $tree^{-1}$ day^{-1} for the control and shade net treatments, respectively. Thus, the average transpiration rates of the trees under the net were around 15% lower than those for trees in the open. An average tree under the net transpired 2 390 litres over the season compared to 2 814 litres in the open. Thus, on average, each tree in the open transpired about 424 litres more than under the net. Tree density in the orchard was about 2

285 trees per hectare. Thus, potential water savings as a result of transpiration reductions in all trees in one hectare can be estimated at around 970 000 L ha^{-1} over the season.

Converting the tree sap flow into equivalent depth units, transpiration under net peaked at 3.3 mm d^{-1} compared to 3.8 mm d^{-1} in the control treatment (Table 22). The average daily transpiration rates were 2.6 and 2.2 mm d^{-1} for the control and netted treatments, respectively. Total transpiration from 28 September 2019 to 5 June 2020 was about 643 mm in the open compared to 546 mm under fixed netting. This amounts to water use rates of about 6429 and 5 462 m^3 ha^{-1}, respectively, and a transpiration-related water saving of 967 m^3 ha^{-1} (-15%). This value for the open orchard compares favourably with the seasonal transpiration values for mature 'Cripps Pink' trees calculated by Gush and Taylor (2014) of 6 870 m^3 ha^{-1}, and by Dzikiti et al. (2018a) of 5 890 m^3 ha^{-1} (October to May).

For the purposes of WP calculations, we show the total seasonal ET in Table 22. The mean values between the two treatments differed by only 0.7%. This is unexpected, and points towards increased orchard floor vegetative growth under nets than in the open (data not shown). The higher vegetation cover on the orchard floor increases the evapotranspiration from the floor which cancels out the benefits from the reduced transpiration under the nets.

4.8.2 Yield, pack out and gross income

We have previously reported detailed results in section 4.7.1.

While yield did not differ markedly between treatments in 2018-2019, fruit size and mass were consistently higher under the nets compared to the open. Consequently, this was the most important factor in the outcome of the fruit grading, together with positive effects of the netting on reductions in sunburn and hail damage. Although small differences in fruit maturity (starch breakdown, TSS) were found between treatments, all fruit still met the requirements for marketing and this did not affect the grading.

After fruit size, the most important quality parameter for 'Rosy Glow' is the peel red colour. To be marketable as Pink Lady®, a high percentage of the fruit surface must be red in addition to meeting all other quality criteria. An apple meeting all other quality criteria but with a lower percentage red cover is marketable as 'Cripps Pink'. In this trial, the laboratory sample indicated a slight reduction in red colour (% cover) under the nets for the first pick which focuses on the outer canopy fruit. This is a common impact of installing protective netting over red and blushed appled cultivars (Mupambi et al., 2018). However, the values for the net treatment were not reduced by a large enough margin to affect potential grading as Pink Lady®. Data from the pack house camera confirmed that 75% of all fruit met the red colour requirement for Pink Lady® in both treatments, irrespective of other defects. Colour was therefore not a factor in the outcome of the grading into four classes, and resulting prices obtained.

The results presented in this section reflect the harvest for the whole orchard in the open and the whole orchard under white nets, as provided by the pack house. The netted treatment resulted in a 29% packout of Pink Lady® as compared to 21% in the open treatment (Table 23). The greatest effect of the netted treatment was in the shift from Class 3 to 'Cripps Pink', compared to the open treatment. This accounted for most of the price differential achieved (Table 23). The price per ton was 24.7% higher in the netted treatment, which translated to a 31.3% higher gross income per hectare relative to the open (control) treatment.

Table 23. *Differences in packout (grading of fruit into four classes) between open and netted treatments, the mean price achieved for each treatment in R t^{-1}, and the gross income per hectare in R ha^{-1}.*

Parameter	2018-2019		2019-2020	
	Open	Netted	Open	Netted
Yield and packout:				
Yield (t ha^{-1})	139	132	113.5	110.6
Class 1 PLD (Pink Lady®)	21%	29%	35%	40%
Class 1 CCP ('Cripps Pink')	36%	51%	55%	52%
Super	3%	0%		
Class 3	41%	20%	10%	8%
Price and gross income:				
Farm gate price (R t^{-1})	R 3 525	R 4 395	R 4905	R 5164
R ha^{-1}	R 465 300	R 610 905	R 556 718	R 571 138

Although the yield in 2019-2020 was similar between the two treatments, mean fruit mass was greater under the net compared to the open. This, together with lower sunburn and hail damage, had a favourable influence on pack out. However, red colour was poorer under the net, which negated some of the positive effects of netting on pack out. Reduced percentage red colour is a common effect of installing protective netting over red and blushed appled cultivars (Mupambi et al., 2018) and was also reported in 2018-2019 in this orchard. However, in 2020 there appeared to be a larger impact of poorer red colour under the net on the pack out compared to 2019.

The netted treatment resulted in a 40% packout of Pink Lady® (Class 1) as compared to 35% in the open treatment (Table 23), whereas the Class 2 ('Cripps Pink') pack out was 52% and 55%, respectively. The net reduced Class 3 pack out from 10% to 8%. The average price per ton (taking into account the pack out) was 5.3% higher in the netted treatment, which translated to a 2.6% higher gross income per hectare relative to the open (control) treatment (Table 23). This was much lower compared to the results reported in 2019.

4.8.3 Water productivity

In 2018-2019, the use of protective white netting (fixed structure) over the 'Rosy Glow' apple orchard at Paardekloof gave rise to an estimated increase in WPp of 5.9% (Table 24). However, the mean yield of the instrumented trees was less than that for the whole orchard. This leads us to conclude that the absolute values calculated for WPp (Table 24) should be viewed with caution (also remembering that we did not obtain a full season of transpiration data), but that the relative change (and especially the direction of change) between the treatments can be used with a higher level of confidence. We can therefore conclude that for this trial the WPp was increased by approximately

6-14% under the fixed white net compared to the open. Conversely, the WUT was decreased by approximately 5-12% (Table 24).

Given the note of caution above, the absolute values or transpiration-based WPp were very comparable to those reported in the previous project (Dzikiti et al., 2018a). For comparable yield (140 t ha^{-1}) of sap flow monitored trees in a mature 'Cripps Pink' orchard in the same production region, the WPp in that project was 21.5 kg m^{-3}. For the whole 'Cripps Pink' orchard in two production regions, yields of 109 t ha^{-1} gave a WPp of 28-29 kg m^{-3} (Midgley et al., 2020).

The WPe was calculated using production and price data for the whole orchard, but transpiration data for the HPV trees, and the absolute values should similarly be viewed with caution. They are, however, highly comparable with the previous project, where the two mature 'Cripps Pink' orchards achieved an WPe of 73-93 R m^{-3}, spanning the value obtained for the control treatment in this project (80 R m^{-3}) (Midgley et al., 2020). The relative difference between the treatments is viewed with confidence. The higher mean price achieved for the fruit grown under the nets, combined with the yield, led to a WPe that was 43.2% higher for the netting treatment (Table 24).

In 2019-2020, the use of protective white netting (fixed structure) over the 'Rosy Glow' apple orchard at Paardekloof gave rise to an estimated increase in WPp of 14.7% (Table 21). This compares favourably to the increase of 14.3% reported in 2018-2019. The lower absolute values for WPp in 2019-2020 compared to 2018-2019 can be explained by the lower yield, together with a slightly higher seasonal transpiration measured over a longer period of the season (starting earlier in spring 2019 compared to spring 2018). The 2019-2020 results increase our confidence in the 2018-2019 results both in terms of the direction of change and the general size of the change between the control and net treatments.

Conversely, the WUT (frequently termed the "water footprint") was decreased by just over 12% in both 2018-2019 and 2019-2020 (Table 24). Again, the absolute values differed between the years, but the relative change was similar.

The WPe was calculated using production and price data for the whole orchard, as in 2018-2019, and the values calculated in 2019-2020 fall within the span of values reported in 2018-2019. However, the difference between the open and netted orchards but smaller in 2019-2020 (21% increase) compared to 2018-2019 (43% increase). This can be attributed to a slightly lower yield under the net, and a much smaller income differential (only 2.6% higher for the net treatment). It must be remembered that a set of theoretical prices per class were used, and the results should be regarded as estimates. The WPe values for 2018-2019 and 2019-2020 compare well with those reported by Midgley et al. (2020) of 73-93 R m^{-3}.

The WPp for the whole orchard, based on both transpiration of the fruit trees, evaporation of the soil, and transpiration of the cover crop and weeds (evapotranspiration), is also shown in Table 24. We found a very small decrease in WPp under the net compared to the open (-1.8%). This resulted from a very small reduction in ET under the net (-0.7%) and a slightly lower yield (-2.6%). Similarly, the WUT increased by 1.9%. The 2.6% increase in gross income in the net treatment led to a 3.4% increase in WPe. These values are not regarded as significant since they likely fall within the margin of error for the raw data. We thus cannot conclude that WP expressed on the basis of evapotranspiration was different under the net compared to the open.

Table 24 Physical Water Productivity, Water Use per Ton, and Economic Water Productivity for the open and fixed net treatments at Paardekloof in the 2019-2020 season, based on measured transpiration (using sap flow measurements) and modelled evapotranspiration (using soil water balance measurements). Calculations were based on the yield of the whole orchard. Transpiration data was in all cases based on 4 instrumented trees per treatment, and evapotranspiration calculations were based on 2 sampling sites per treatment. The percentage change for netting compared to open is also indicated. Previous results for 2019 (transpiration-based only) are included for comparative purposes.

Year	**Physical Water Productivity ($kg\ m^{-3}$)**			**Water Use per Ton ($m^3\ t^{-1}$)**			**Economic Water Productivity ($R\ m^{-3}$)**		
Transpiration-based	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**
2019	22.8	26.0	14.3	43.9	38.4	-12.5	80.1	114.6	43.2
2020	17.7	20.3	14.7	56.6	49.4	-12.8	86.6	104.6	20.8
Evapotranspiration-based	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**
2020	11.4	11.2	-1.8	87.4	89.0	1.9	56.1	58.0	3.4

4.9 MODELLING WATER USE OF APPLE ORCHARDS UNDER FIXED NETTING

The parameters of the generic Shuttleworth and Wallace water use model are shown in Table 25. Detailed descritions of the parameters are given in Dzikiti et al. (2018a).

Table 25 Parameters for the dual source evapotranspiration model applied to apple trees under fixed and draped nets.

Parameter	Description	Default value
b_1	Value of soil surface when ϴ15 = $ϴ_{FC}$(in sm^{-1})	50
b_2	Describe the non-linear changes in surface resistance with soil moisture (-)	-5.83
β	Describe the curvature of f(ϴ) (-)	0.1
K	Extinction coefficient	0.6
Kvpd	Describe the influence of the VPD stress factor	1.33
Kr	Describe the curvature of f(Rs) (in Wm^{-2})	10
r_{ST}	Minimum stomatal resistance for apple trees (in sm^{-1})	80
SWC_FC_15	Field capacity at 15 cm	0.12
SWC_FC	Soil water content at field capacity for whole profile	0.12
SWC_WP	Soil water content at permanent wilting point (cm^3/cm^3)	0.02
T_{max}	Maximum temperature for complete stomatal closure (in °C)	45
T_{min}	Minimum temperature at which stomatal close (in °C)	3
T_{opt}	Optimum temperature for growth of the trees (in °C)	20.5

These parameters were applied to the two treatments (i.e. control and fixed nets) without modification. Data for the 2019-2020 growing season were used and details of the actual water use and environmental measurements have been presented above. Given the small size of the orchards, whole orchard evapotranspiration was determined using the universal soil water balance approach. The presence of the shade nets also made the use of the more accurate and direct micrometeorological techniques such as the eddy covariance or surface renewal methods impossible since free air flow above the orchard was not possible. So the modelled orchard ET were compared to the soil water balance derived ET which provided the best independent data set. Besides the fact that the soil water balance approach is another model, the main source of uncertainty with the soil water balance approach used here was the inability to account accurately for the drainage component which we suspect was significant for the irrigated crops growing on sandy soils.

4.9.1 Modelling water use for the control treatment

The typical partitioning of evapotranspiration into daily transpiration and soil evaporation (Es) for the ‘Rosy Glow’ control orchard is shown in Figure 76. In this and the subsequent sections, the soil evaporation component lumps together all water losses from the orchard floor, i.e. evaporation from the bare soil and from other orchard artefacts such as weeds, cover crops, mulches, etc. The data is for the period 01 October 2019 to 30 June 2020.

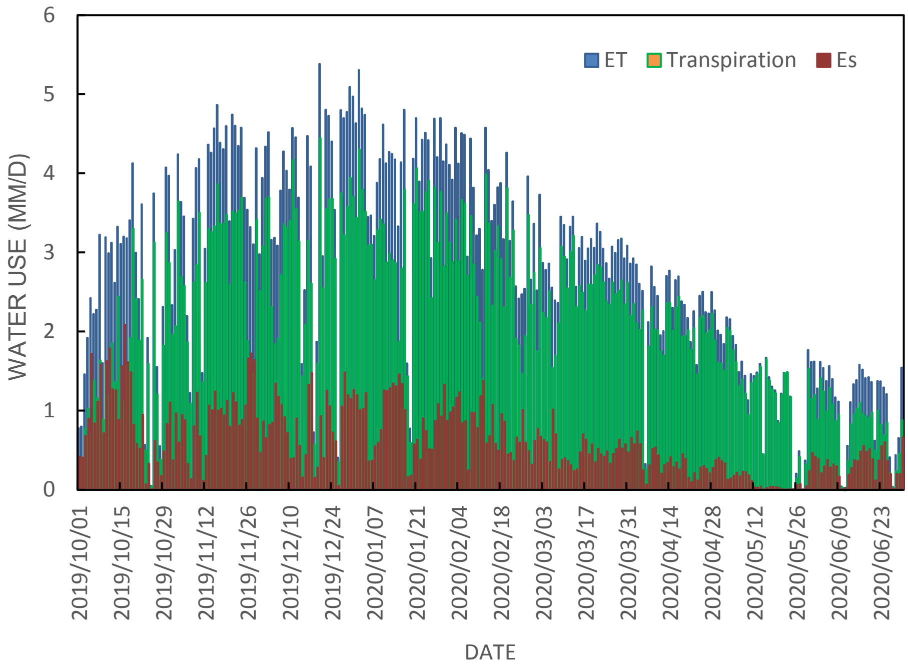


Figure 76 Orchard evapotranspiration and its constituent components for the control 'Rosy Glow' orchard at the fixed nets site determined using a dual source ET model for the 2019-2020 growing season.

As expected soil evaporation is highest at the start of the season when tree canopy cover was minimum gradually declining as the leaf area index increased. The increase in the transpiring leaf area coincided with the increase in atmospheric evaporative demand as we transitioned from spring to the hot summer weather. Towards the end of the season (autumn to winter), orchard floor evaporation rates declined substantially due in part to the reduced irrigation levels and hence a drier soil and also because of the declining atmospheric evaporative demand. The onset of the winter rains in late May to early June saw a modest rise in the orchard floor evaporation rates. For most of the season, the model predicted that tree transpiration had the largest contribution to the orchard evapotranspiration. The 'Rosy Glow' trees maintained their leaves well into the winter season which explains the non-zero transpiration rates in the winter months.

The modelled transpiration for the open/control 'Rosy Glow' orchard was within 20% of the sap flow measured transpiration (Figure 77) with a coefficient of determination around 56%. Figure 78 shows the comparison between the measured and modelled whole orchard evapotranspiration for the control treatment at the fixed nets site.

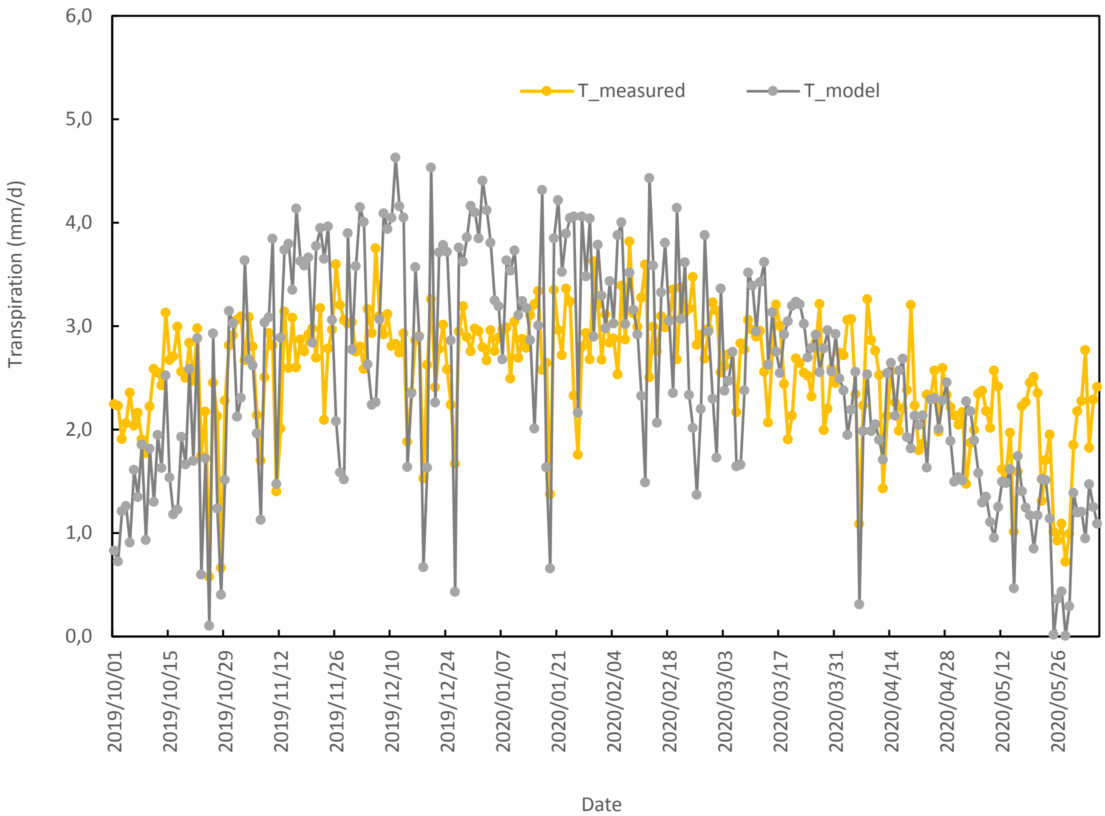


Figure 77 Comparison of the transpiration simulated using the dual source model and the measured values for the control treatment under the fixed nets.

The soil water balance derived and modelled ET values were of the same order of magnitude as shown by the monthly total water use data presented in Figure 78. The two methods agreed to within less than 5% of each other with the model explaining over 97% variations in the SWB ET. This high level of accuracy of the dual source model is not surprising as the model has previously been successfully validated in 12 orchards with different canopy cover in the previous WRC/Hortgro apples project (Dzikiti et al., 2018b).

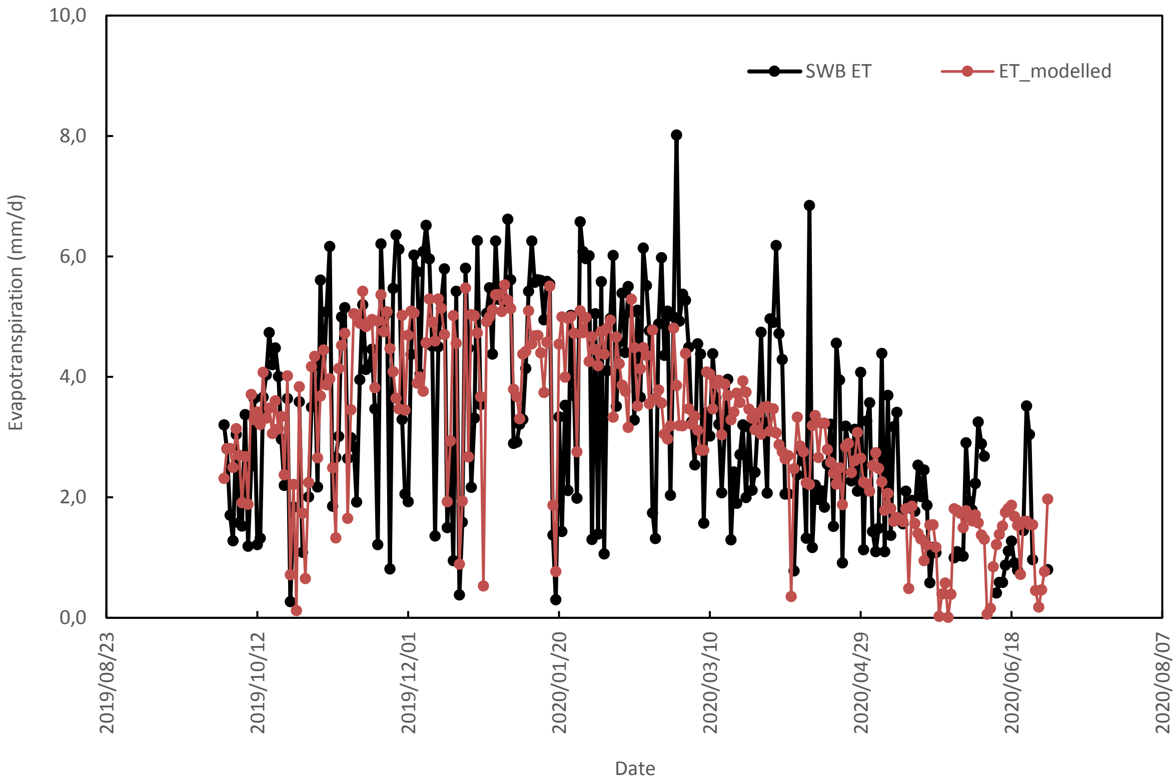


Figure 78 Comparison of evapotranspiration of the control treatment at the fixed net site determined using the soil water balance and dual source model.

The monthly crop water requirements for the open 'Rosy Glow' orchard ranged from 790-870 m^3/ha at the start of the season in October, rising to between 1 330-1350 m^3/ha during the peak summer season in January (Table 26). The observed soil evaporation in Table 26 was calculated as the difference between SWB derived ET and the sap flow derived transpiration values.

Table 26. Monthly water requirements determined using the soil water balance approach and by the dual source ET model.

	Observed			**Modelled**		
	ET (mm)	**Transpiration (mm)**	**Es (mm)**	**ET (mm)**	**Transpiration (mm)**	**Es (mm)**
Oct-19	79	71	7,7	87	49	38
Nov-19	122	83	39,4	124	90	34
Dec-19	127	85	41,4	131	100	31
Jan-20	133	88	44,6	135	104	31
Feb-20	128	91	37,0	117	88	30
Mar-20	103	82	21,2	108	87	21
Apr-20	81	71	9,5	79	63	16
May-20	48	55		46	37	9
Jun-20	36			39	28	11

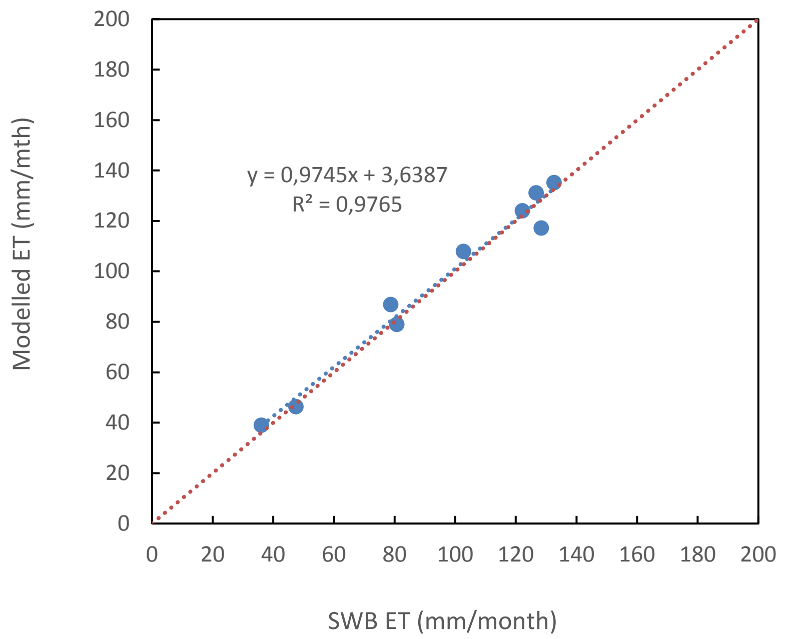


Figure 79 Monthly orchard water requirements determined by the dual source ET model and the soil water balance approach at the fixed nets site.

The dotted orange line in Figure 79 denotes the 1:1 line. The modelled seasonal total crop water requirement was 8 660 m^3/ha which was not different from the soil water balance estimate of 8 570 m^3/ha.

4.9.2 Modelling water use under fixed nets

The partitioning of the modelled orchard water use for the 'Rosy Glow' trees under fixed nets were similar to that predicted for the open control treatment (Figure 80). As expected the tree transpiration component had the largest contribution to the orchard ET for most of the season. Daily transpiration was reasonably well predicted by the model (Figure 81) with a slope close to 1.0 (of 0.98), and intercept close to zero (of 0.19). The R^2 was somewhat low at about 0.51 and the cause of the relatively large scatter is unclear. Independent model parameterization seems to be necessary to accurately model the water use dynamics under the fixed nets. The model significantly under estimated evapotranspiration under the nets especially during the peak summer season as shown in Figure 82 and Figure 83. Given that transpiration was fairly well predicted under the fixed nets, the underestimation in ET is most likely due to the difficulties in accurately modelling the orchard floor evaporation component (Es). Soil water balance ET data presented earlier in this report suggested that there was greater understorey evapotranspiration under the nets due to enhanced growth of the understorey vegetation. This could be a contributory factor in the ET model performance.

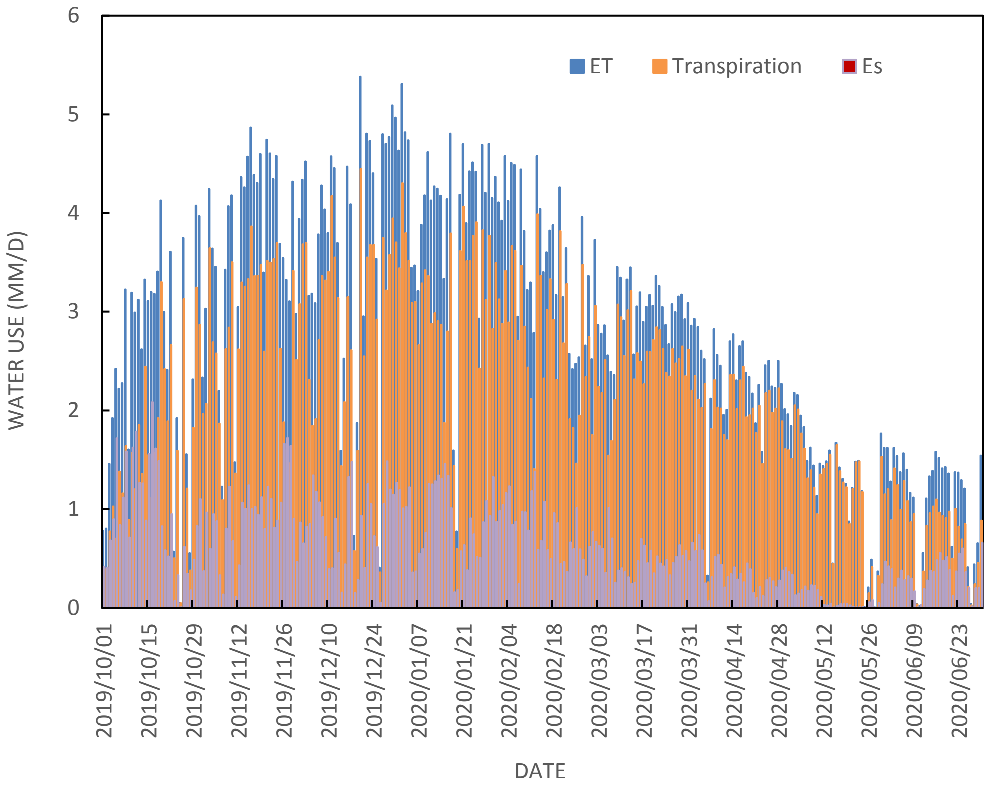


Figure 80 Partitioning of water use of a 'Rosy Glow' orchards under the fixed nets at Paardekloof during the 2019-2020 growing season.

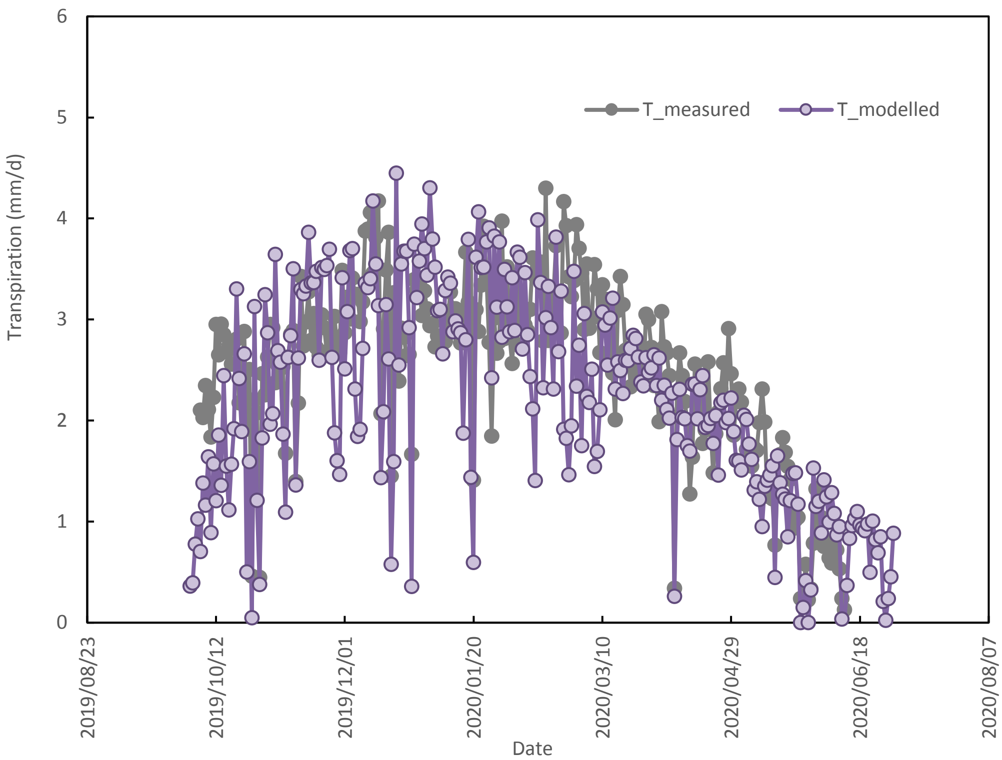


Figure 81 Comparison of the measured and modelled transpiration of 'Rosy Glow' trees under fixed netting.

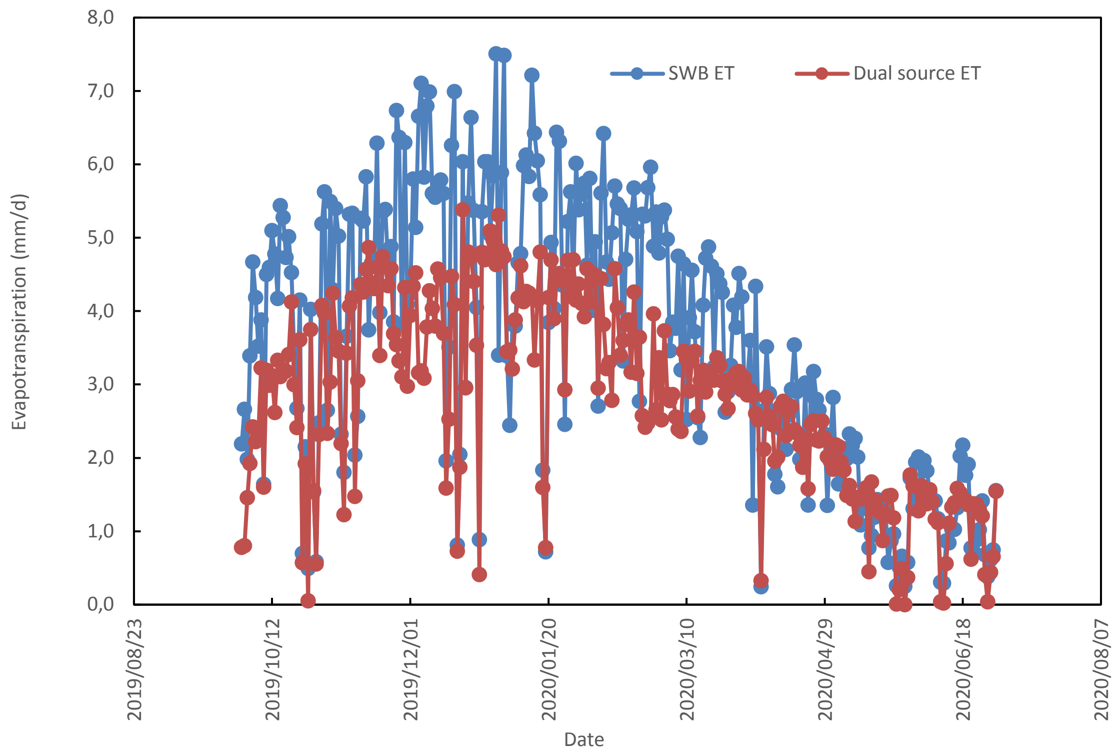


Figure 82 Comparison of the soil water balance with the modelled evapotranspiration under fixed nets.

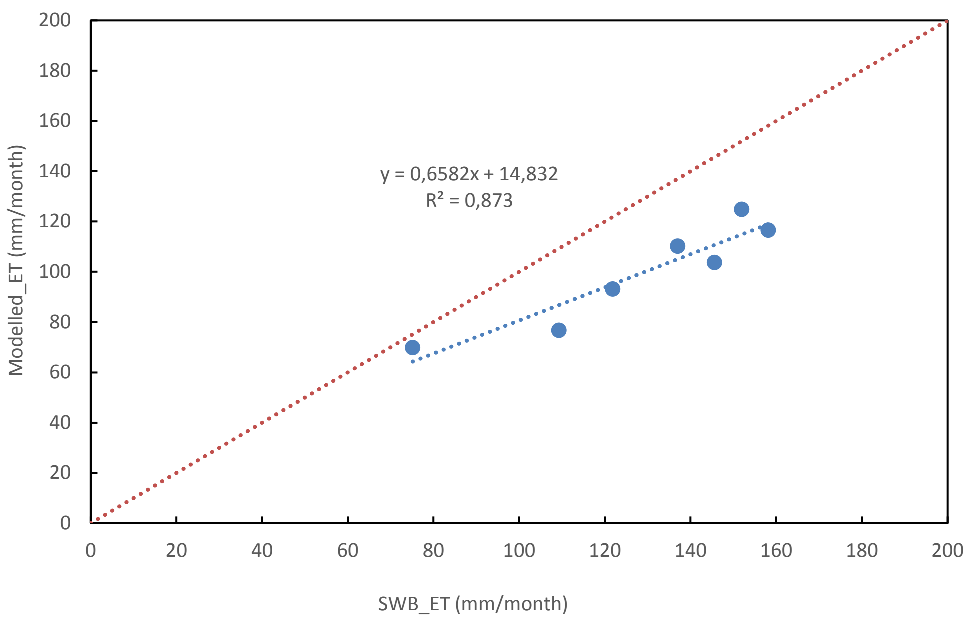


Figure 83 Comparison of monthly total evapotranspiration determined using the soil water balance approach and modelled using the dua source model.

4.9.3 Crop coefficients

The ten-day averaged K_c values for the control for the 2019-2020 season increased during the early fruit and canopy development stage in October from 0.37 reaching 1.13 during the mid-season stage (Figure 84).

The basal crop coefficient (K_{cb}) was calculated only for the 2019-2020 season. In the open (control) treatment K_{cb} amounted to 0.62 in October and remained relatively constant at 0.56-0.59 from November until February, where after it increased to 0.79 in April (Table 27). The mean monthly K_{cb} in the control was 0.63. The K_{cb} for the netted orchard increased gradually from October (0.48) to April (0.66). The mean monthly K_{cb} was 0.55 in the netted orchard.

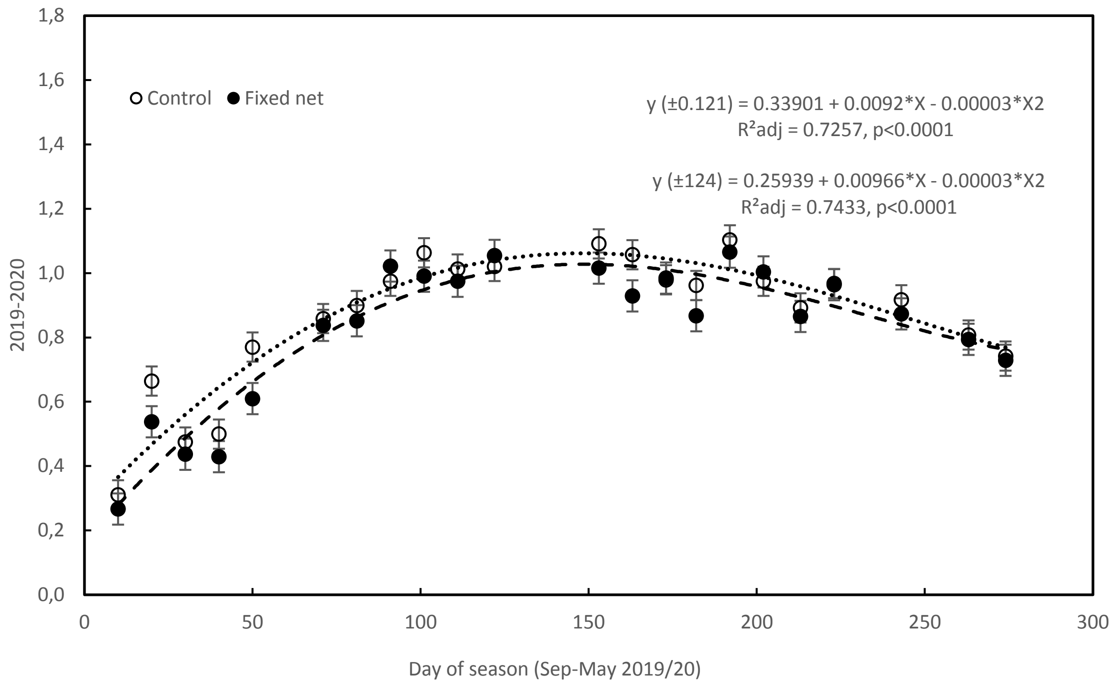


Figure 84 Seasonal changes in the 10-day crop coefficients (Kc) for the control and net treatments in 'Rosy Glow' apple orchards under fixed nets in the 2019-2020 season. The 10-day Kc averages were calculated for days on which the soil water balance was considered to be in equilibrium. The first day of the season was taken as 1 September.

Table 27 Monthly basal crop coefficients (Kcb) and their standard error (SE) calculated from sap flow derived transpiration (T) values for the control and net treatments in 'Rosy Glow' apple trees in the 2019-2020 season during the irrigation period.

Month	T_Control mm d^{-1}	T_Net mm d^{-1}	Kcb_Control	Kcb_Control SE	Kcb_Net	Kcb_Net SE
Oct	2.24	1.75	0.62	±0.02	0.48	±0.02
Nov	2.73	2.39	0.59	±0.02	0.52	±0.02
Dec	2.69	2.52	0.56	±0.02	0.52	±0.01
Jan	2.80	2.64	0.59	±0.02	0.54	±0.02
Feb	2.98	2.75	0.59	±0.02	0.54	±0.01
Mar	2.62	2.40	0.68	±0.02	0.62	±0.01
Apr	2.18	1.82	0.79	±0.01	0.66	±0.01

4.10 BUDGETING LIFETIME COSTS AND INCOME OF ORCHARDS IN THE OPEN AND UNDER FIXED NETTING

Table 28 Cumulative profit per scenario for open and netted 'Rosy Glow' apple orchards. The light grey scenarios (top section) are based on the actual orchard used in the study, starting in 2010. The dark grey scenarios (bottom section) are a theoretical orchard planted in 2020.

	Open	Net	Difference
Scenario 1A	R 6 659 408	R 7 905 653	R 1 246 245
Scenario 2A	R 6 659 408	R 7 577 465	R 918 057
Scenario 1B	R 4 821 405	R 5 853 786	R 1 032 381
Scenario 2B	R 4 821 405	R 5 525 599	R 704 194
Scenario 3	R 6 511 308	R 7 121 486	R 610 178
Scenario 4	R 6 511 308	R 6 793 299	R 281 991
Scenario 5	R 4 596 581	R 6 101 297	R 1 504 716
Scenario 6	R 4 596 581	R 5 566 715	R 970 134
Scenario 7A	R 4 462 205	R 6 101 297	R 1 639 092
Scenario 8A	R 4 462 205	R 5 566 715	R 1 104 510
Scenario 7B	R 4 291 982	R 6 101 297	R 1 809 315
Scenario 8B	R 4 291 982	R 5 566 715	R 1 274 733

The 'Rosy Glow' orchards (netted and open) at Paardekloof were established in 2010. The loss in profit seen in Figure 85 to Figure 90 in Year 4 (2013) was due to hail damage. Towards the end of 2014, one half of the orchard was covered with shade netting, and this caused the dip in profit. In Year 7 the yield was lower in the open section compared to the netted section. Following some adjustments in orchard management, good yields started to be achieved in both orchards, with higher profits seen in the netted orchard in Years 8 and 10 based on larger fruit with less hail and sunburn damage. However, issues with red colour losses under the net negated the benefits in Years 9 and 11 (2020). If better fruit quality under the net can be achieved consistently in the future (by dealing with the colour issue), annual profit should be higher (Figure 85, Scenario 1A) and lead to a significant difference between the treatments in cumulative profit (Table 28).

One replacement of the fixed netting in Year 15 reduces the potential for cumulative profit (Figure 86, Scenario 2A) in this orchard, but the difference is still significant, based on the achievement of consistently better pack out and high yield under the net.

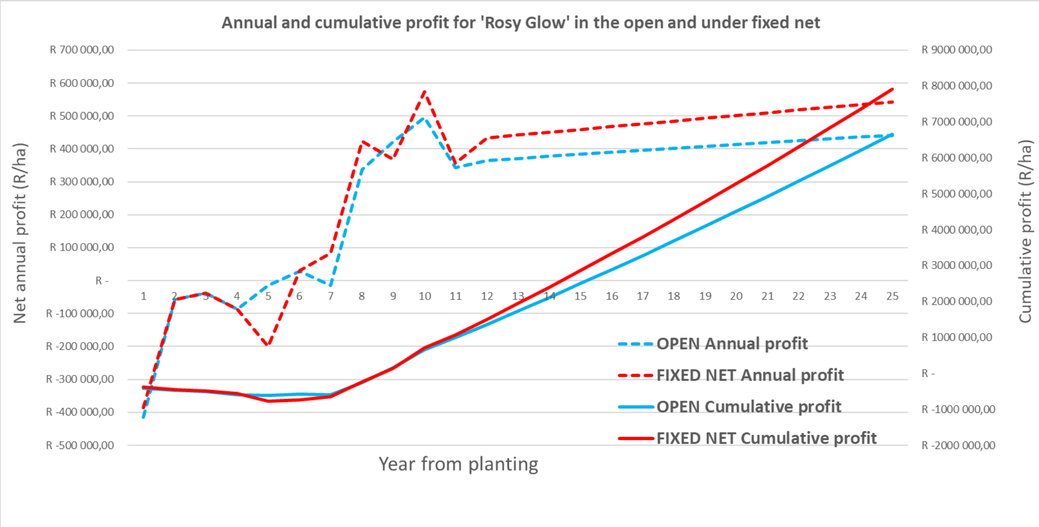


Figure 85 Net annual and cumulative profit for a 'Rosy Glow' apple orchard under Scenario 1A.

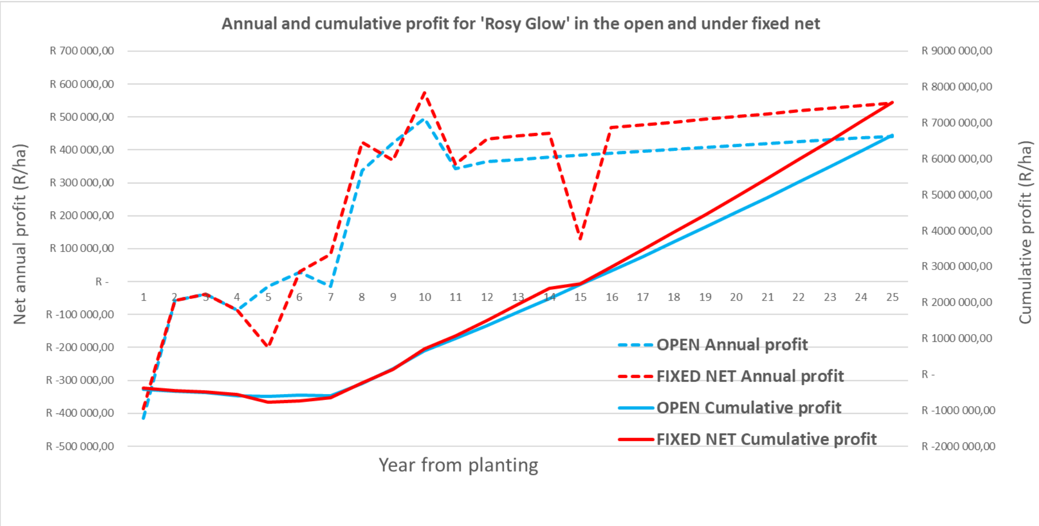


Figure 86 Net annual and cumulative profit for a 'Rosy Glow' apple orchard under Scenario 2A.

While maintaining the quality benefit of nets is important, the yield benefit is also significant, as seen in Figure 87 and Figure 88. In these scenarios (1B and 2B), future yield was 90 t/ha, with the same quality benefits as in Scenarios 1A and 2A. Profit is clearly lower and the differential between net and open is reduced (Table 28).

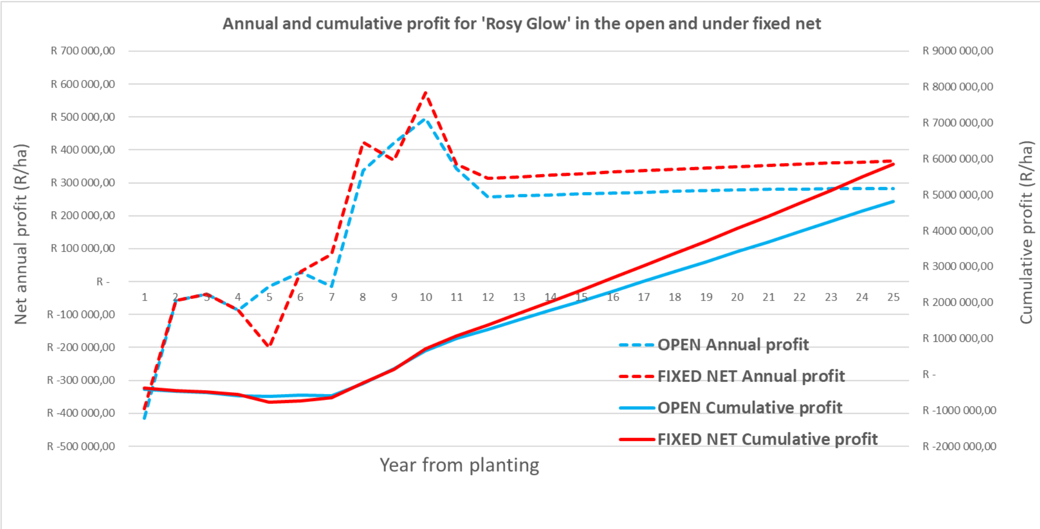


Figure 87 Net annual and cumulative profit for a 'Rosy Glow' apple orchard under Scenario 1B.

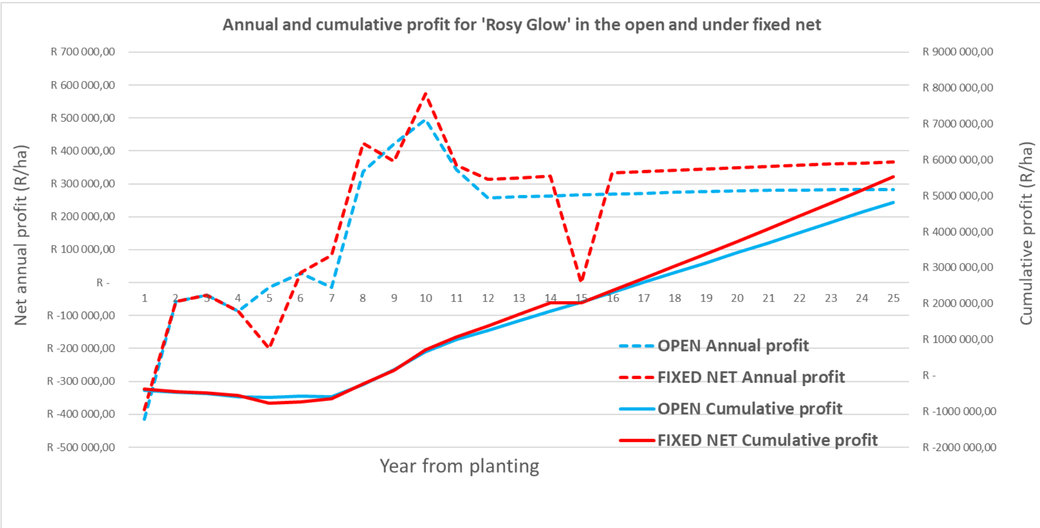


Figure 88 Net annual and cumulative profit for a 'Rosy Glow' apple orchard under Scenario 2B.

In Scenarios 3 and 4 we assume a smaller benefit of netting to fruit quality and packout in this orchard going forward, while still achieving high yield. The difference in cumulative profit between the treatments (Scenario 3, Figure 89) is halved relative to Scenario 1A, and when a net replacement is factored in (Scenario 4, Figure 90), the financial benefit over the orchard lifetime is only around R 282 000 (Table 28).

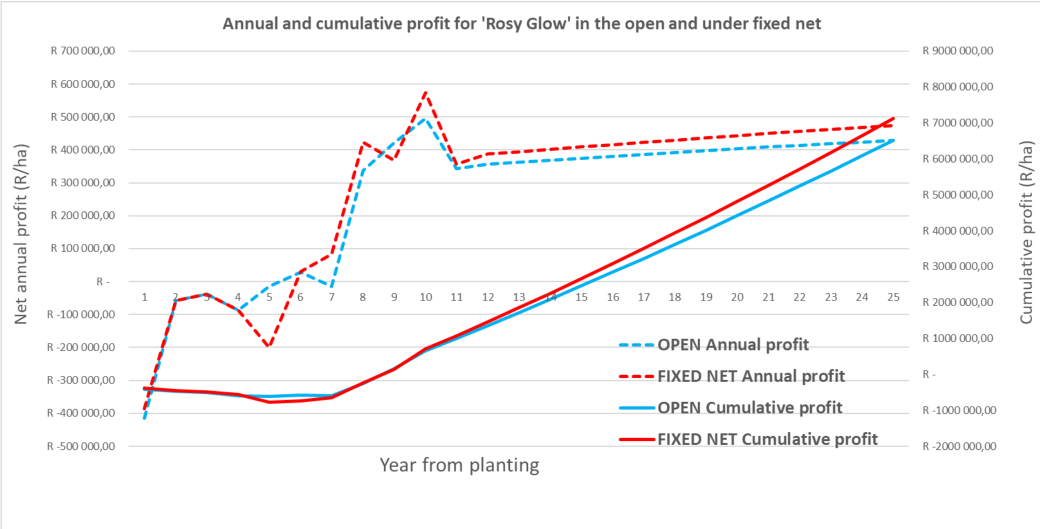


Figure 89 Net annual and cumulative profit for a 'Rosy Glow' apple orchard under Scenario 3.

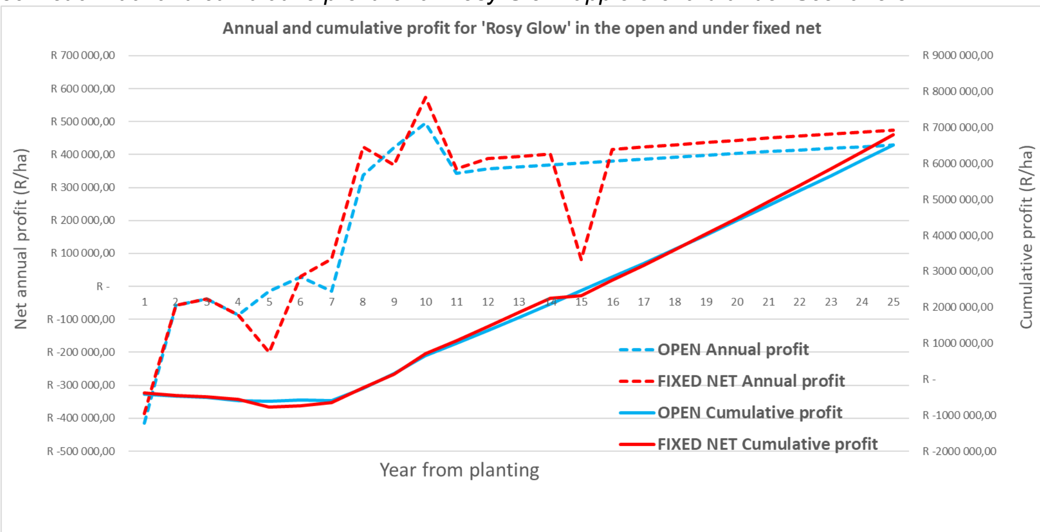


Figure 90 Net annual and cumulative profit for a 'Rosy Glow' apple orchard under Scenario 4.

The following sets of figures (Figure 91 to Figure 96) show the results of modeling scenarios 5-8, which simulate a theoretical new planting of 'Rosy Glow' in 2020, with or without nets. Standard assumptions used by Dutoit Agri for planning purposes are used. In this set, we test the change in profitability when known risks mitigated by nets (hail and sunburn) are included in the simulations either once or twice during the orchard lifetime.

Figure 91 and Figure 92 show the baseline profit difference between netted and open orchards when no serious hail or sunburn losses (20% orchard cull and only 30% Class 1) are experienced. Cumulative profit is around R4.6 million (open) and R6.1 million (netted), the latter being reduced to R5.6 million if the net is replaced once (Table 28). With one hail/sunburn event, the open orchard cumulative profit is reduced to R4.5 million (Figure 93), and with two events it is reduced to R4.3 million (Figure 95). Under the net, cumulative profit remains at R6.1 million (R5.6 million with net replacement) (Figure 93 to Figure 96) under the assumption that the net successfully protects the whole crop. This results in an increase in the profit differential between open and netted orchards (Table 28).

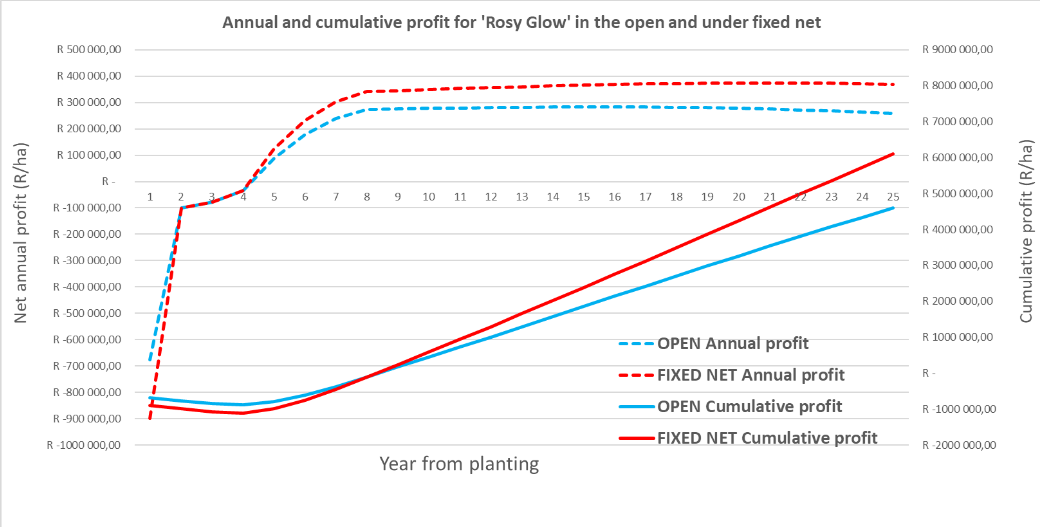


Figure 91 Net annual and cumulative profit for a ‘Rosy Glow’ apple orchard under Scenario 5.

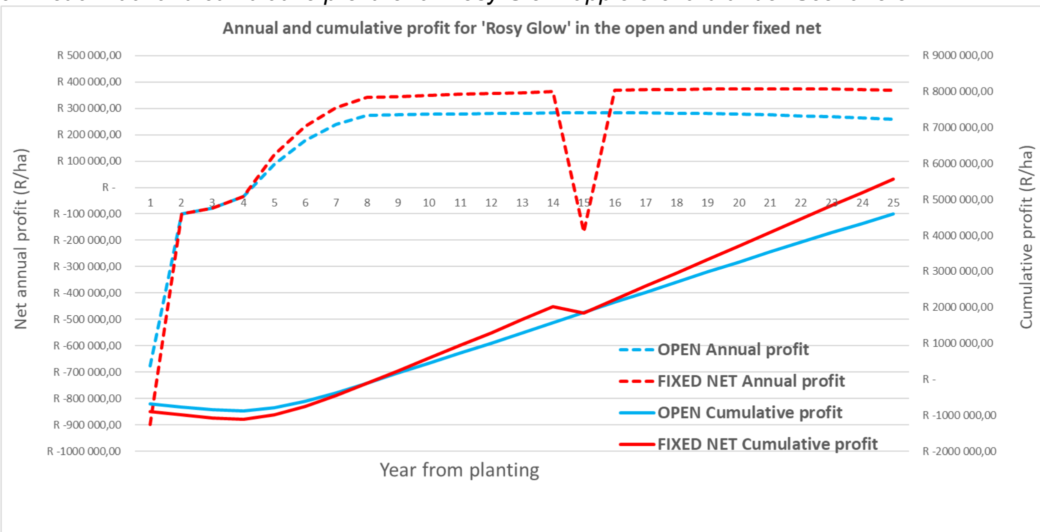


Figure 92 Net annual and cumulative profit for a ‘Rosy Glow’ apple orchard under Scenario 6.

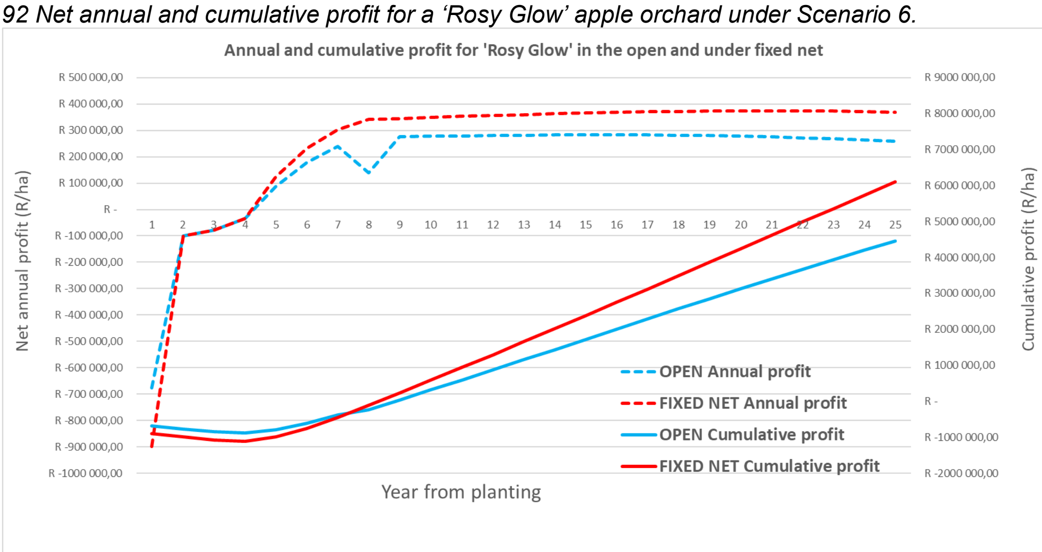


Figure 93 Net annual and cumulative profit for a ‘Rosy Glow’ apple orchard under Scenario 7A.

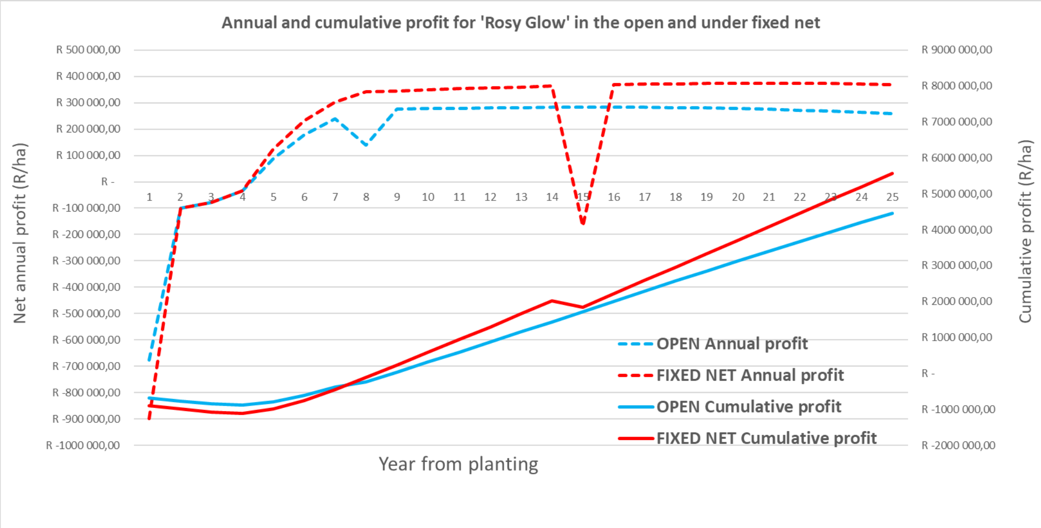


Figure 94 Net annual and cumulative profit for a 'Rosy Glow' apple orchard under Scenario 8A.

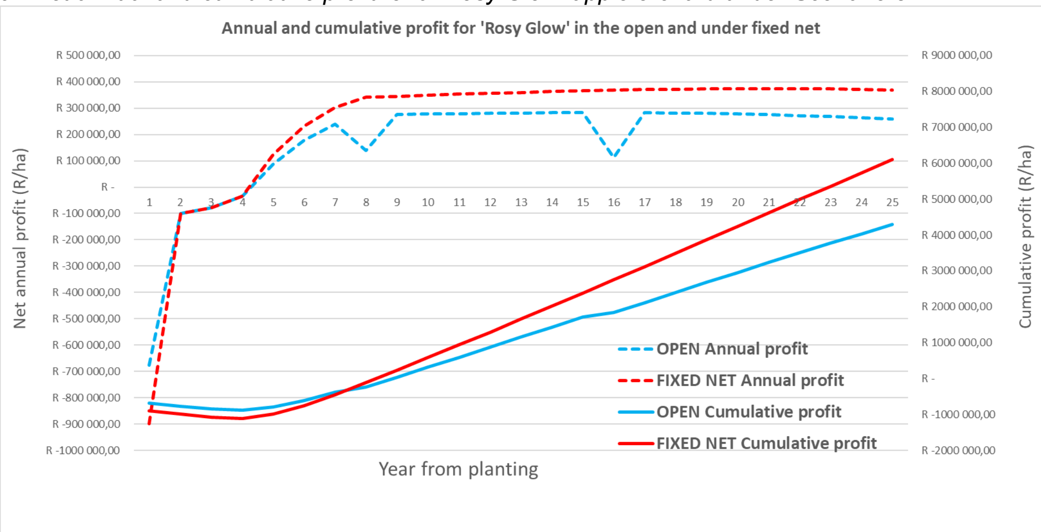


Figure 95 Net annual and cumulative profit for a 'Rosy Glow' apple orchard under Scenario 7B.

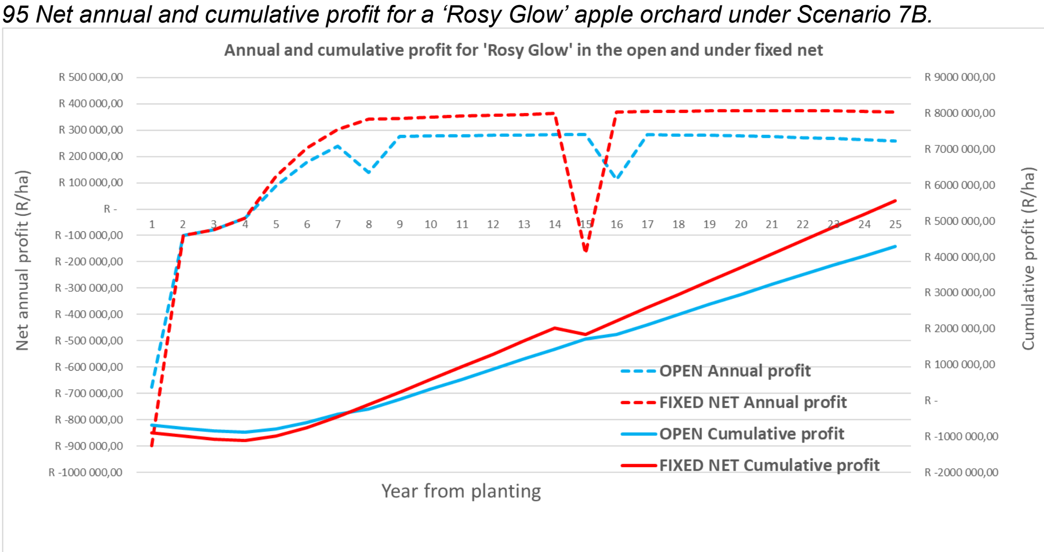


Figure 96 Net annual and cumulative profit for a 'Rosy Glow' apple orchard under Scenario 8B.

CHAPTER 5: RESULTS AND DISCUSSION – DRAPED NETTING TRIALS

5.1 ORCHARD MICROCLIMATE

5.1.1 Orchard microclimate – Paardekloof (KBV)

5.1.1.1 Solar radiation

The draped nets were installed in the 'Golden Delicious Reinders' orchard at Paardekloof on 27 November 2019 after fruit drop. They were removed on 26 February 2020 prior to harvest. Physical details of the draped nets were given in Chapter 3 of this report. The impact of the nets on the radiation microclimate are shown Figure 97. Prior to the installation of the nets for the period late October to late November, the daily total solar radiation was almost similar between the two treatments with peak radiation around 32.3 MJ/m^2/d on 25 November 2019. Minor differences in the irradiance values can be attributed to lack of sensor levelness and to obstruction by canopy artefacts.

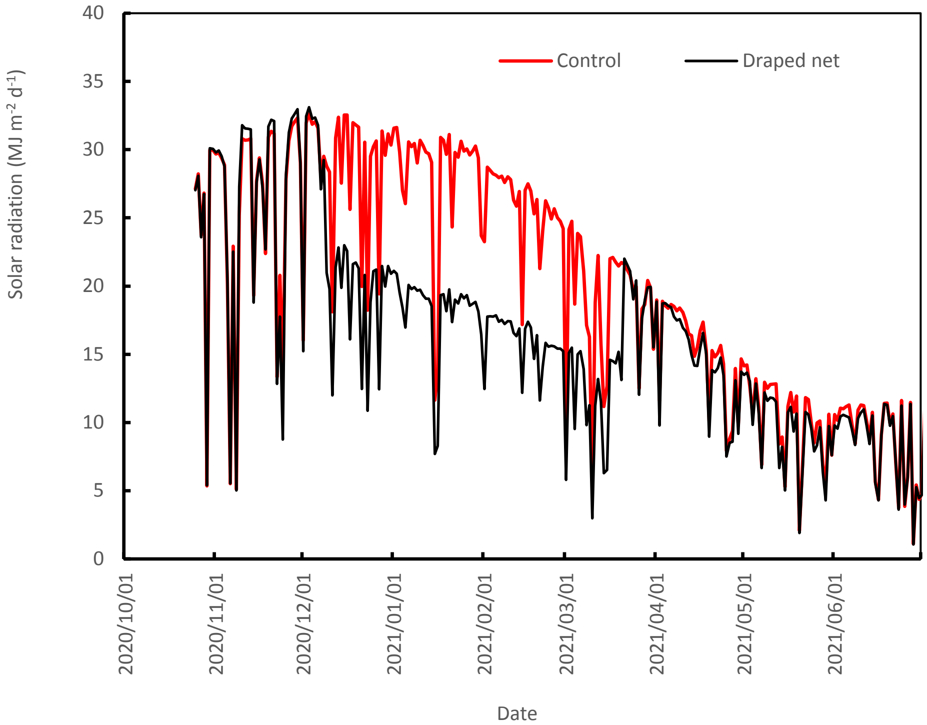


Figure 97 Comparison of the daily total solar radiation for the control and draped nets treatments at Paardekloof.

The draped nets reduced the radiation intensity under the nets by between 8 and 11.5 MJ/m^2/d on clear days representing between 30 and 35% reductions. This is clearly illustrated in Figure 98 which shows differences between the daily total radiation under the nets and in the open.

Key physiological processes that determine plant performance, e.g. transpiration and photosynthesis, are influenced by the quality and intensity of radiation. We explore the impact of the reduced radiation on these processes in the next sections.

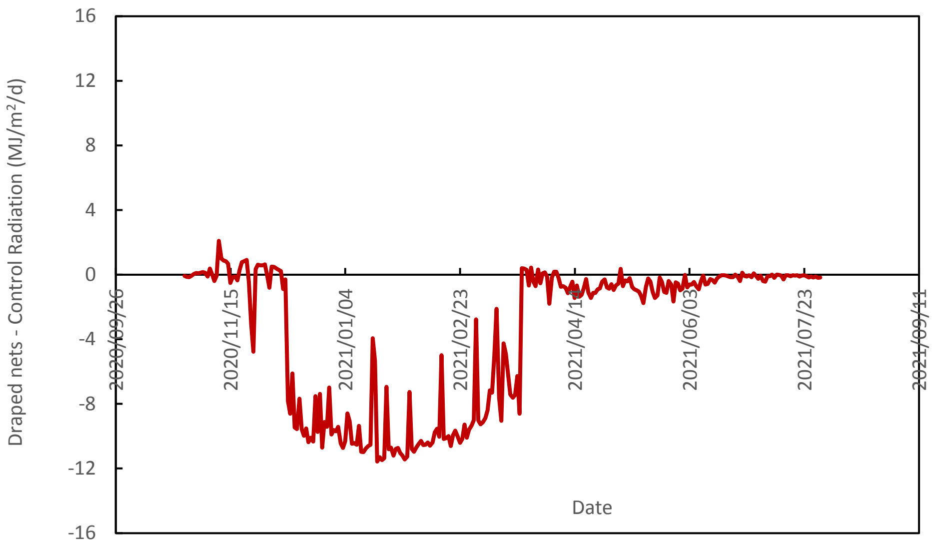


Figure 98 Difference between the solar radiation under draped nets and in the control orchard at Paardekloof.

5.1.1.2 Air temperature, relative humidity and vapour pressure deficit

The temperature, humidity, and vapour pressure deficit (Figure 99) for the Paardekloof data did not show the impact of the draped nets, which was unexpected. The control treatment temperature remained 1 to 2°C warmer than the draped nets, while the relative humidity was consistently 5 to 10% higher under the draped nets for the entire measurement period. This lack of difference in the temperature and humidity variables was evident even when differences were plotted between the two treatments (data not shown). The reduction in radiation intensity surely should affect the canopy temperature somewhat, but this doesn’t seem to be the case for unclear reasons. One possible explanation is that the control treatment weather station was in a mature ‘Rosy Glow’ orchard while the draped nets were in the ‘Golden Delicious Reinders’ orchard.

These data suggest that there are significant differences in the canopy microclimates for trees with different canopy size, as the ‘Rosy Glow’ canopy tended to be more open than the ‘Golden Delicious Reinders’. Ideally, the control weather station should have been in the same orchard under the draped nets treatment to eliminate any bias due to tree size differences or other factors. The second possible explanation could be that the area between the two treatments had a small dam separating them. The control weather station was upwind of the dam, while the draped net weather station was downwind. Given that the prevailing wind at the site was from the control to the draped nets, funnelled by the relief of the area, it is probable that the draped nets trial was in a vapour blanket of the dam. This could explain the consistently high relative humidity and low temperature even before the nets were installed, but further investigations are needed.

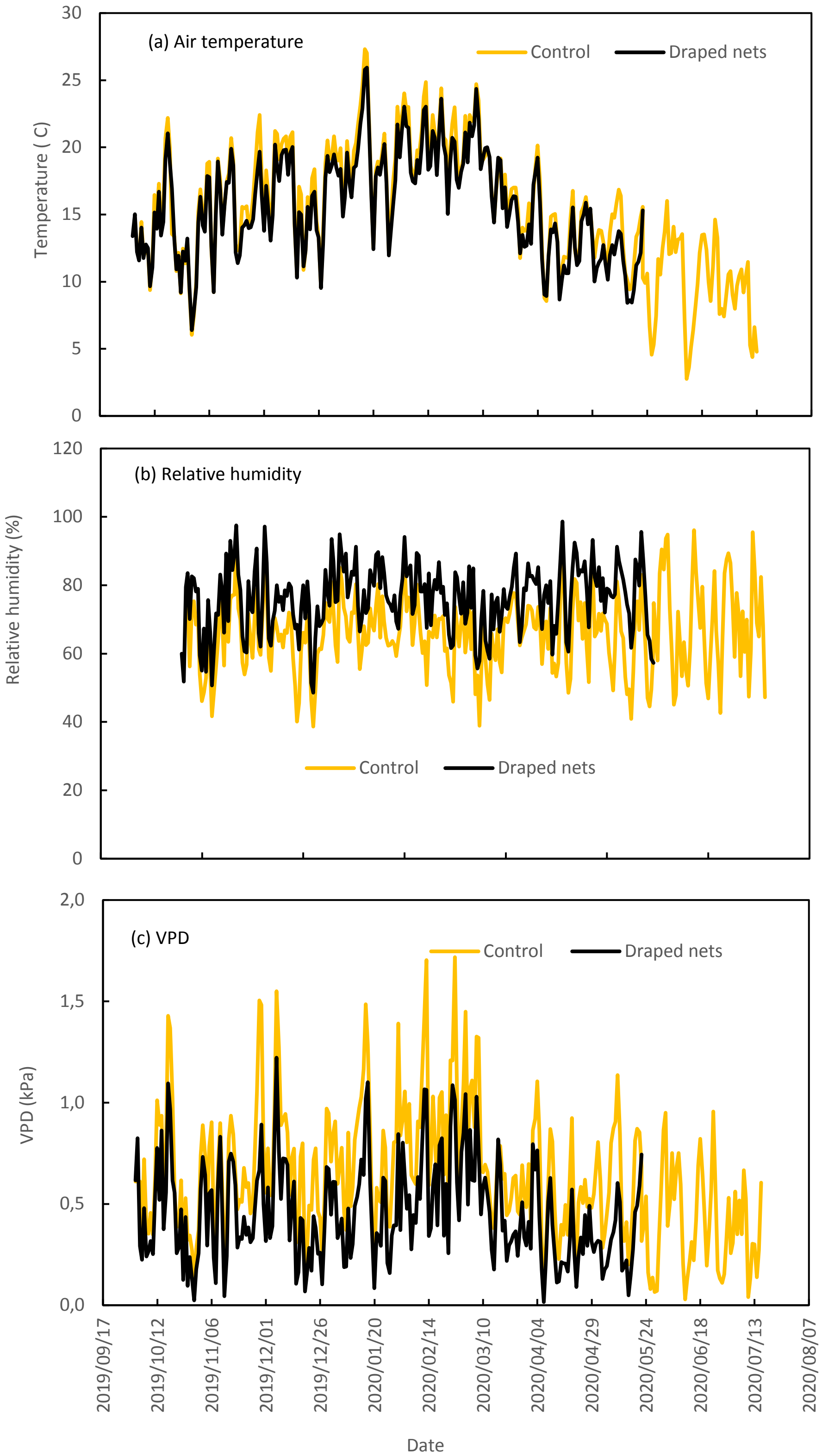


Figure 99 Comparison of the temperature and humidity microclimates under draped nets and in the control orchard at Paardekloof.

5.1.1.3 Windspeed and reference evapotranspiration

As expected, the presence of the nets reduced the windspeed within the tree canopies (Figure 100a). The wind speeds tended to be greater at the start and end of the season when the leaf area is smaller. The tree leaves obstruct the air flow thereby reducing the windspeeds. Overall, the difference in the windspeeds when the nets were installed was smaller because of the already low values.

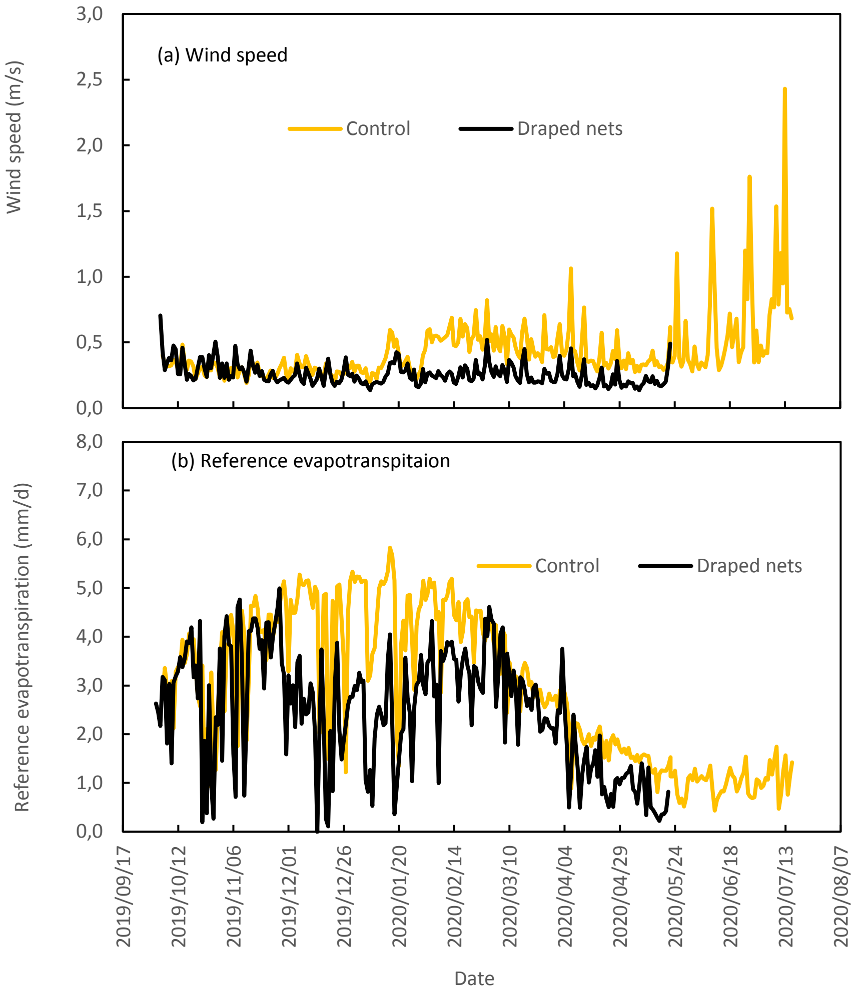


Figure 100 Effect of draped nets on; (a) the wind speed, and (b) reference evapotranspiration.

Of all the weather variables, it appears that the reduction in solar radiation had the greatest effect on the within canopy atmospheric evaporative demand, depicted by the ET_o (Figure 100b). Peak ET_o for the control was around 5.8 mm/d reached on 15 January 2020. The corresponding peak under the draped nets was around 4.1 mm/d representing a 30% decline due to the presence of the nets. The order of magnitude of the decline in ET_o due to the nets matches that of the decline in daily total solar radiation (30-35%) reported earlier confirming that the reduction in solar radiation is the main driver in the changes in the canopy microclimate under draped nets.

5.1.2 Orchard microclimate – Southfield (EGVV)

5.1.2.1 Solar radiation

A similar effect of the draped nets on the daily total solar radiation was observed at Southfield as at Paardekloof (Figure 101 & Figure 102a). As reported earlier, the draped nets were installed on 17 December 2020 and removed on 09 March 2021p. Unlike at Paardekloof, in Southfield the draped net and control weather stations were in the same 'Golden Delicious' orchard. So, the canopy microclimates were comparable. The region highlighted in light blue in Figure 101 and Figure 102 indicates the period when the nets were over the trees. Total duration for the period under nets was two and a half months in the summer (77 days). The daily total solar radiation was similar between the two treatments before and after installation of the draped nets (Figure 102a). On average, the maximum difference between the two treatments without the nets was within ±0.3 MJ/m^2/d. This can be attributed to the lack of levelness of the sensors since the two pyranometers were cross calibrated against each other prior to installation. Vibrations in the canopy due to wind and farm machinery also caused occasional displacement of the sensors from the horizontal positions. Overall, the draped nets reduced the daily total solar radiation by between 8.0 and 10.0 MJ/m^2/d translating to about 30 to 37% reduction in the radiation intensity under the nets. These values are somewhat higher than the screening factor which was about 24%, according to the manufacturers. The reason is likely related to the angle at which the sun's rays hit the net and the uneven orientation ("waviness") caused by the draping.

5.1.2.2 Air temperature, relative humidity and vapour pressure deficit

The reduction in solar radiation under nets has implications on other climate variables and the physiological responses of the trees. The baseline data prior to net installation and after the nets were removed showed minor differences in key canopy microclimate variables. For example, the maximum air temperatures were within ±1.0 °C of each other while the difference in relative humidity between the treatments was less than ±2% without the nets. Minor fluctuations in the baseline data are expected as no two trees have the same canopy microclimates. The maximum daytime air temperature (Figure 101b), RH (Figure 101c), and wind speed (Figure 101d) all responded to the presence of the draped nets. The air temperature decreased by up to 3.4 °C due to the presence of the nets. The RH, on the other hand, was higher under the nets by up to 3% (Figure 102). This is because of the cooler temperatures and the reduced air circulation which trapped the moisture under the nets.

The combined effects of the changes in temperature and humidity regimes under the draped nets was a reduction in the VPD of the air under the nets, by at most 0.1 kPa. The magnitude of the difference in air temperature and RH, and hence the VPD, showed a clear seasonal effect as illustrated in Figure 102c. The greatest reduction in air temperature and increase in RH was largest during the peak summer period (around 14 January 2021). This suggests that the draped nets have a significant effect in moderating extreme temperature and this is in contrast with the results of the fixed nets (Chapter 4). Under the fixed nets, differences in microclimatic conditions were in fact smallest during peak summer and maximum early and late in the season. The within canopy windspeeds were higher early and late in the growing season when the canopies were leafless, consistent with the observations at Paardekloof (Figure 101d). The difference in the windspeed due to the draped nets was not as apparent due to the low wind speed regimes within the tree canopies due to obstruction by canopy artefacts which was greatest during the active growing season.

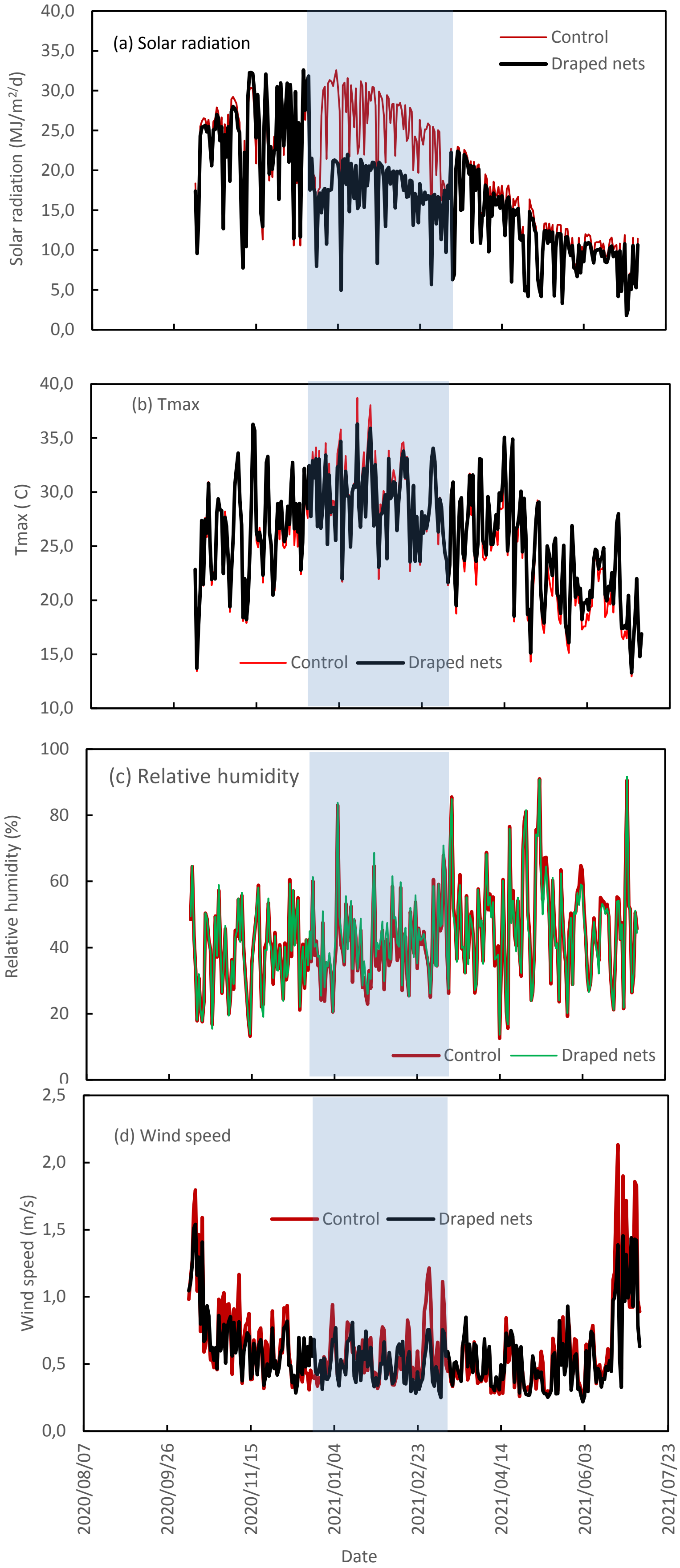


Figure 101 Effect of the draped nets on the canopy microclimate representing (a) the solar radiation, (b) maximum temperature, (c) minimum relative humidity, and (d) wind speed.

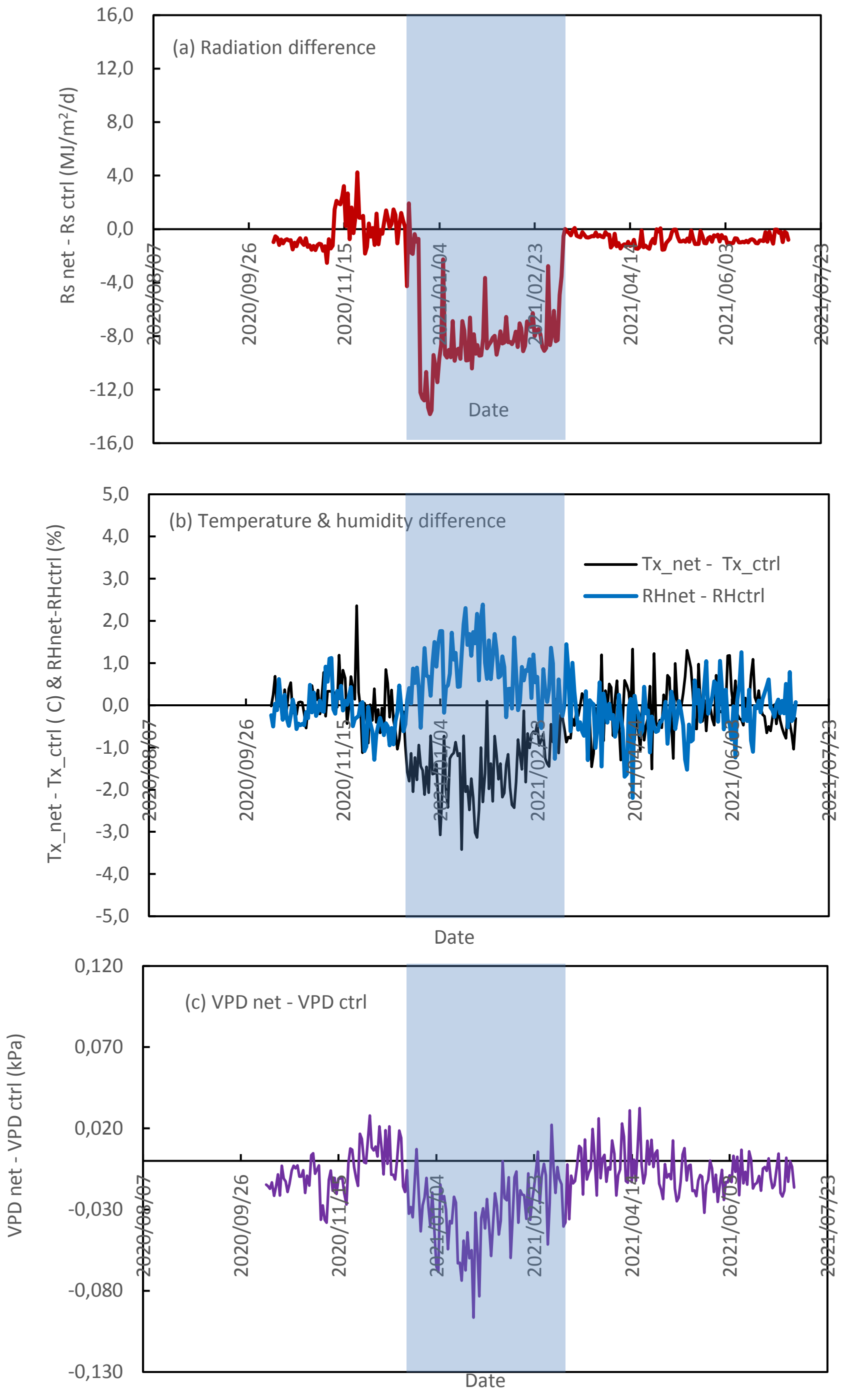


Figure 102 Differences in the microclimate between the draped nets and control treatments representing (a) the solar radiation, (b) air temperature and relative humidity, and (c) vapour pressure deficit of the air.

5.1.2.3 Atmospheric evaporative demand

The draped nets had a clear effect on the reference evapotranspiration in the 'Golden Delicious' orchard at Southfield, Villiersdorp (Figure 103). These results are similar to those reported for Paardekloof, and the reduction is driven mostly by the lower radiation intensity under the draped nets. The contributions of the reduced windspeed, vapour pressure deficit of the air, etc. on the reduction in ET_o are quite small. Rather, the reduction in the radiation intensity has the greatest effect on the atmospheric evaporative demand under the nets. The peak daily ET_o for the control was 6.6

mm/d compared to about 4.1 mm/d under the draped nets. This represents a 37% reduction which is the same order of magnitude as the reduction in solar radiation due to the draped nets.

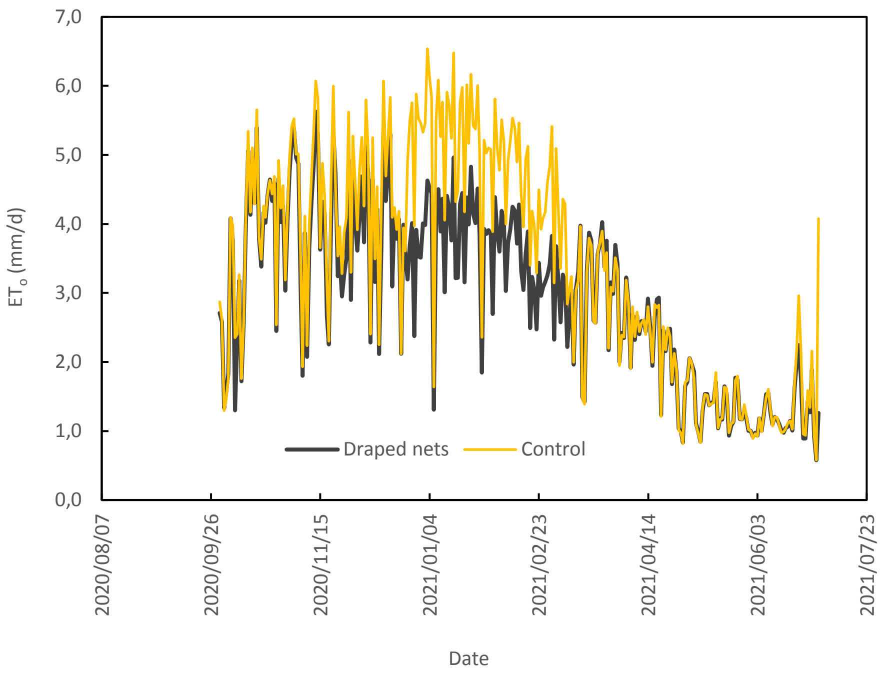


Figure 103 Effect of the draped nets on the reference evapotranspiration at Southfield.

5.2 SOIL PROPERTIES, SOIL WATER CONTENT AND IRRIGATION

5.2.1 Soil and irrigation – Paardekloof (KBV)

5.2.1.1 Soil physical properties

Soil of the open section was classed according to *particle size* (Soil Classification Working Group, 1991) as sandy loam in the top 300 mm and from 900-1200 mm, and as loamy sand for the 300 to 900 mm depth increment (Appendix G, Table 56). Soil in the draped net section had loamy sand up to 1.2 m deep. The open (control) section contained on average for the 1.2 m deep soil profile slightly less clay and silt (14.5%) compared to below draped net (18%). Although the medium sand fraction in the open and under net was comparable (on average 7.1%), the former section had 5.4% more fine and 1.9% less coarse soil than the latter. Stone content was higher in the draped net section (1.5%) compared to the open (0.3%) (Figure 104).

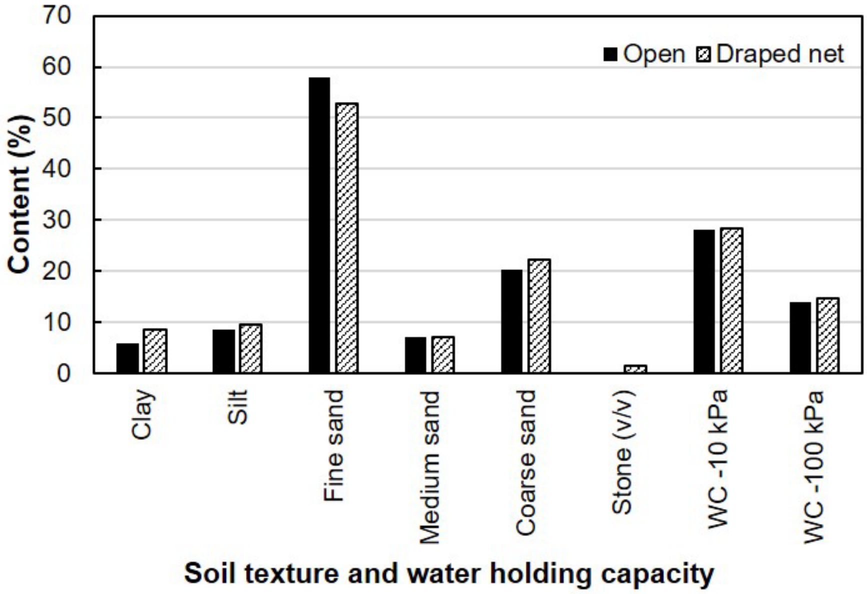


Figure 104 Soil particle size distribution and water content (WC) at -10 kPa and -100 kPa for the open (control) and draped net areas in the 'Golden Delicious Reinders' orchard at Paardekloof in 2019-2020. Soils were sampled in the ridge and data averages represent the soil profile up to a 1.2 m depth.

Bulk density ranged between 1.27 and 1.7 in the ridge, 1.40 and 1.65 in the tractor track and 1.42 and 1.65 g cm^{-3} in the cover crop area (Figure 105). Bulk density in the draped net section compared to the control was higher at the 200 mm depth in the tractor track and cover crop area, and at the 600 mm depth in the ridge and tractor track. Deeper in the soil profile bulk density was comparable for the draped net and open sections. On average for both sections, bulk density in the tractor track (1.53 g cm^{-3}) and cover crop (1.54 g cm^{-3}) was higher compared to that in the ridge (1.4 g cm^{-3}).

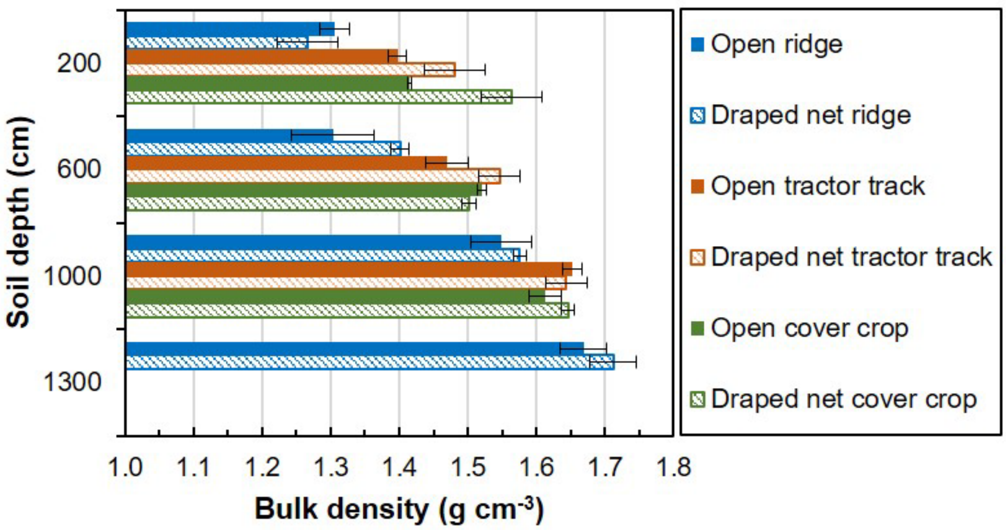


Figure 105 Bulk density of sandy soil at the 200, 600, 1000 and 1300 mm depths in the ridge, tractor track and cover crop areas, respectively, of the control and draped net 'Golden Delicious Reinders' orchard at Paardekloof in 2019-2020.

A soil water retention curve for the orchard was obtained by combining data for the 300, 600 and 900 mm depths sampled at the open and draped net sections of the orchard (Figure 106).

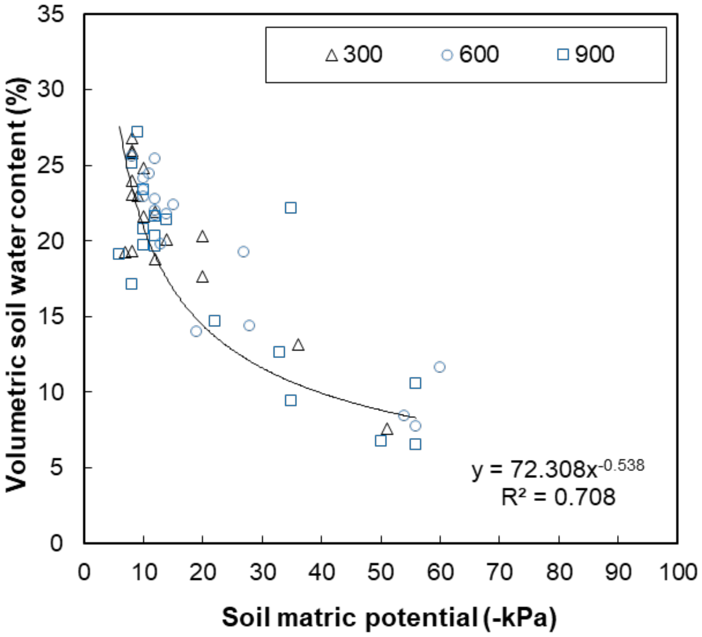


Figure 106 Soil water retention curve determined for a 0.9 m sandy loam to loamy sand soil profile at the 'Golden Delicious Reinders' draped net orchard, with gravimetric samples taken from the open and draped netting sections to establish the in situ retention curve.

For the 'Golden Delicious Reinders' orchard, according to the commercial laboratory, volumetric soil water retained at -10 kPa was 28.2% in the open and 28.3% for the draped net section, which is a bit higher than the 20.3% and 21.7% estimated according to Saxton et al. (1986). Soil water retained at -10 kPa according to the *in situ* retention curve, i.e. 21%, agreed well with that estimated according to Saxton et al. (1986). The soil water holding capacity between -10 and -100 kPa was estimated by the commercial laboratory from texture as 143.1 and 135.2 mm m^{-1} for the open and fixed net orchard sections, respectively. According to Saxton et al. (1986) these amounts were 75 and 74.1 mm m^{-1}, and the plant total available water between -10 and -1500 kPa for the open and netted sections, respectively, 128.6 and129.6 mm m^{-1}. In this case the estimate from the *in situ* retention curve of available water between -10 and -100 kPa, (149 mm m^{-1}) agreed better with the estimate from the commercial laboratory than with Saxton et al. (1986). However, the *in situ* retention curve needs further refinement to enable reliable estimates of the soil water holding capacity.

5.2.1.2 Soil water content dynamics and irrigation

Comparison of volumetric soil water content calculated from the CS616 period using the manufacturer's calibration and actual soil water content at comparable CS616 periods indicated that the manufacturer's calibration in general underestimated the volumetric soil water content (Appendix F, Figure 143). The *CS616 in situ calibration* statistics for sensors at each soil water balance site at the 'Golden Delicious Reinders' orchard (Appendix F, Figure 142) indicated that calibrations between gravimetrically determined volumetric soil water content and CS616 period obtained accuracy equal to or better than the 2.5% indicated by the manufacturer. The periods were restricted to the low range between 17.7 and 24.9 μs. Outliers removed were attributed to variation in spatial distribution of soil water along the length of the sensor prongs and/or variation in stone content of the sampled area vs sensor location.

Soil water dynamics for the different orchard areas for the ***control*** treatment showed comparable water content in the ridge, tractor track and cover crop areas at the beginning of the season after significant rainfall during winter (Figure 107a).

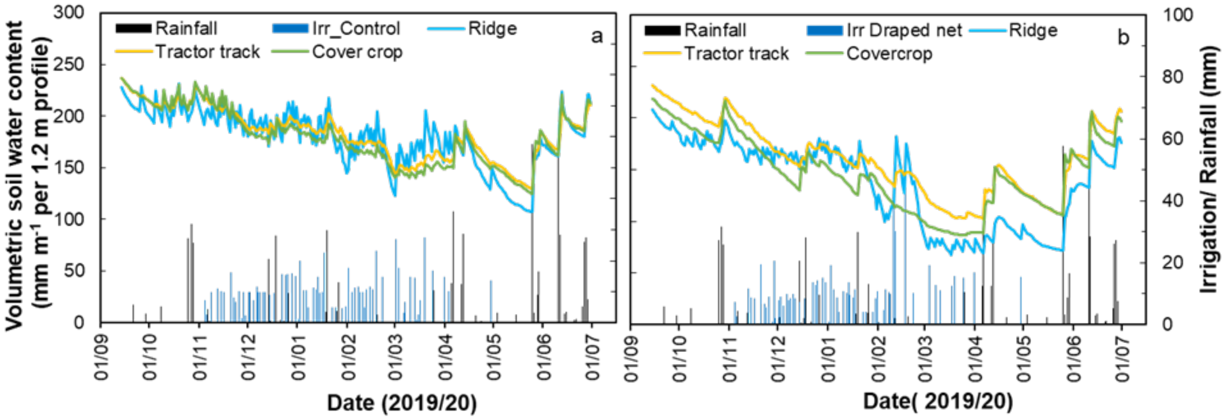


Figure 107. Soil water content (midnight) dynamics for the 'Golden Delicious Reinders' (a) control treatment and (b) draped net treatment for ridge, tractor track and cover crop orchard areas for the period 14/09/2019-30/06/2020 during the 2019-2020 season.

From the end of October though it appeared as if the soil water content in the ridge tended to decrease gradually – almost on a monthly basis – towards the end of February (Figure 107a). Significant rainfall that occurred during middle December and January tended to stem this trend, but the soil water content decreased further in February. From the beginning of March (after the harvest on 26 February) the soil water content gradually increased towards the beginning of April. Rainfall occurred on 5-6 April and 11-12 April and regular irrigation was halted, but after that the soil water content tended to decrease steeply until 14 mm irrigation increased the soil water content in the ridge slightly on 29 April.

For the ridge, soil water content decreased sharply from 20 January until 2 February when less than the monthly average irrigation per irrigation event was applied between 22 and 30 January (Table 29) after 29 mm rainfall occurred on 19 January, and 13 mm on 26 January. Soil water content also decreased steeply between 23 February and 1 March when no irrigation was applied probably to accommodate the harvest period. The tractor track and cover crop generally had similar, but slightly drier, trends compared to the ridge, with the cover crop area having the lowest water status from November until 5 April. Irrigation events were reflected in the soil water content response of these orchard areas, although not as strongly as for the ridge.

For the ***draped net*** treatment there was a slight decrease in ridge soil water content from October to November (Figure 107b). After the installation of the draped net at the end of November, the soil water content remained stable or even improved until the 10th of January after which a decreasing soil water content trend started. This trend was stemmed by rainfall that occurred on 19 and 26 January and was finally corrected by irrigations of 38 and 30 mm on 10 and 11 February, respectively. After that followed another decreasing trend with irrigations of 44 mm and 10 mm applied on 17 and 22 February, respectively.

Table 29. Monthly mean amount per irrigation event (±standard error or SE), number and interval of irrigations applied to the control and fixed net treatments at the 'Golden Delicious Reinders' orchard, Paardekloof during 2019-2020. Irrigation applied is indicated as mm per full surface area. Data are also supplied for selected periods.

Month/Period	Irrigation amount (mm d^{-1})				Number (n)		Interval (d)	
	Control		Draped net		Control	Draped net	Control	Draped net
	Mean	SE	Mean	SE				
October	0.04	-	0.1	-	1	1	31	31
November	8.2	1.1	8.6	1.8	13	12	2.3	2.5
December	11.6	0.8	10.2	0.7	15	15	2.1	2.1
January	9.1	1.5	8.3	1.2	16	17	1.9	1.8
February	11.3	1.5	14.6	4.7	13	11	2.2	2.6
March	12.9	2.6	11.5	2.3	12	9	3.4	9.0
April	11.9	1.8	7.8	7.6	2	2	15.0	15.0
22/01-30/01/2020	4.9	0.1	5.3	1.1	4	4	2.3	2.3

No irrigation between 22 February and 2 March (harvest and net removal on 26 February) resulted in a steep decrease in soil water content (Figure 107b). Several irrigations applied after this period were unable to restore the soil water content significantly. Significant rainfall on 5-6 and 11-12 April raised the soil water content somewhat, but due to application of only one irrigation near end April the soil water content remained low until near end May and early June when significant rainfall eventually refilled the soil profile gradually. Soil water content in the tractor track and cover crop areas was higher compared to the ridge from the beginning of the season. However, a general decreasing soil water content trend over the season was evident from end October until 5 April. Soil water content dynamics mainly reflected rainfall and also responded to significant irrigation events. During March the soil water content in the tractor track and cover crop area tended to level off, indicating very dry conditions in the soil profile.

If *soil water dynamics per soil depth* are considered, the soil water content for the ***control*** treatment at the 200 mm depth tended to gradually decrease but remained relatively high from end of October until 20 January 2020 (Figure 108a). A steep drop in soil water content at the 200 mm depth followed until 2 February after which it was restored.

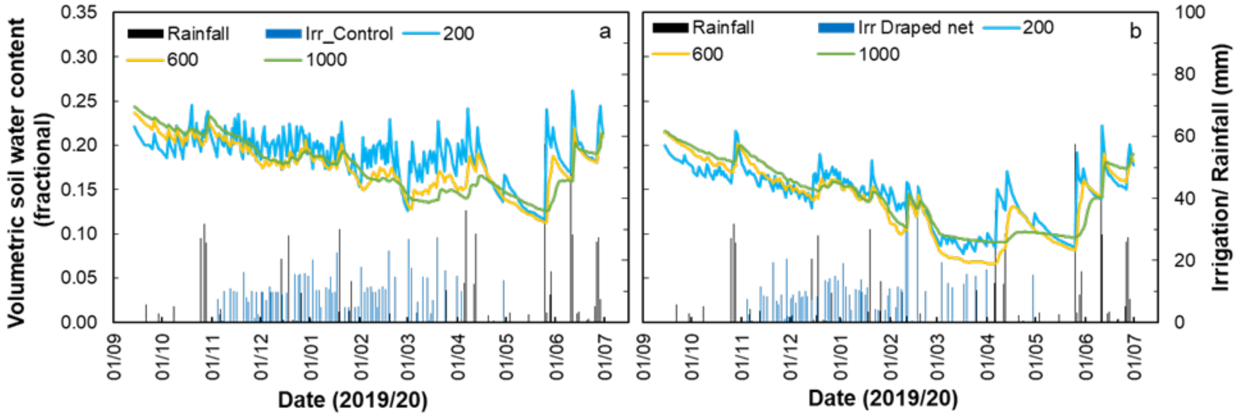


Figure 108. Soil water content (midnight) dynamics for the 'Golden Delicious Reinders' (a) control treatment and (b) draped net treatment averaged over orchards areas at the 200 mm, 600 mm and 1000 mm depths for the period 14/09/2019-30/06/2020 during the 2019-2020 season.

The soil water content remained relatively stable until a period of no irrigation occurred between 23 February and 3 March (harvest), which resulted in another steep drop in soil water content. From the beginning of March the soil water content tended to gradually increase again until the beginning of April. As discussed previously, lack of rainfall and irrigation resulted in very low soil water content during April and May, and the soil profile was only refilled from end June and during July (Figure 108a). Soil water content at the 600 mm and 1 m depths was lower compared to the 200 mm depth from about the beginning of December and followed each other closely until 22 January 2020. After this period the 600 mm trend tended to reflect irrigations whereas the 1 m depth displayed a gradual drying trend over time until the beginning of April. For the rest of the season the soil water content at the 600 mm and 1 m depths more or less followed the trend at the 200 mm depth, although it did not respond to the irrigation applied near end April.

For the ***draped net*** treatment the soil water content at the 200 mm depth tended to decrease from end October until 14 December, after which it improved slightly (Figure 108b). However, it decreased again gradually until 22 February, after which it decreased drastically and remained low between 3 March and 5 April. Although rainfall early in April improved the soil water status, lack of irrigation and other rainfall events during April and May resulted in low soil water status, which was only rectified after significant rains near end May and in June. Soil water content at the 600 mm and 1 m depths followed the same but showed a smoother trend than at the 200 mm depth. Although the soil water content trend at these depths tended to be higher than at the 200 mm depth earlier in the season it became lower from 14 December until no irrigation was applied near end-February (coinciding with the harvest on 25 February). The soil water content at these depths leveled off at low levels from 1 March until 5 April, after which rainfall improved soil water content. Significant rainfall near end May and in June was required to restore the soil water content at the 600 mm and 1 m depths to their water status at the beginning of the season.

Soil water dynamics for the soil profile up to 1.2 m deep indicated that, despite differences in volumetric soil water content, seasonal trends in soil water content for the control and draped net site was in general similar (Figure 109). The control treatment soil water content did reflect rainfall and irrigation events clearer compared to the draped net treatment. Furthermore, the draped net site displayed prominent periods of lower soil water content compared to the control from 1-10 February and 2 March until 5 April 2020. The control treatment displayed an increasing trend in soil water content during the latter period.

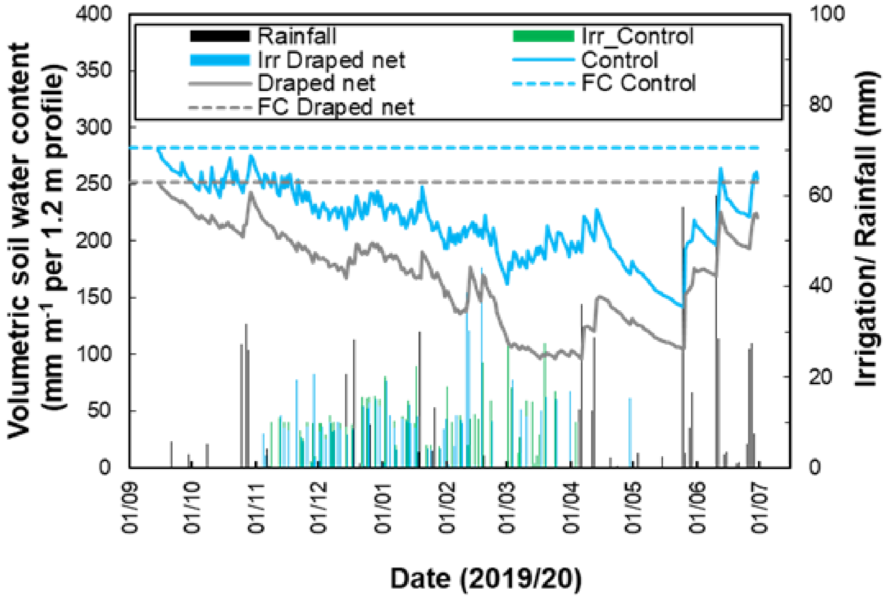


Figure 109. Soil water content (midnight) dynamics, rainfall and irrigation applied for the 'Golden Delicious Reinders' control and draped net treatments for the period 14/09/2019-30/06/2020 during the 2019-2020 season. The field capacity (FC) values determined from hourly soil water content graph trends are also indicated.

5.2.2 Soil and irrigation – Southfield (EGVV)

5.2.2.1 Soil physical properties

For the main root zone up to 900 mm deep, the soil in the open (control) and under draped net contained on average 16.7% clay and 8.7% silt and were classed according to particle size (Soil Classification Working Group, 1991) as sandy loam (Appendix G, Table 57, Figure 110). The soil in the open section contained 1.3% less clay/ silt and 2.9% less fine sand, but 2.3% and 3.2% more medium and coarse sand compared to the netted section. The soil contained no stones. At the 900 mm to 1.2 m depth increment the clay content decreased to 10% and silt to 2-4%. For the open section this layer was classed as loam coarse sand as it contained less fine (2.4%) and medium (4.2%) and 4.6% more coarse sand compared to the netted section (sandy loam). The water holding capacity of the soil up to 900 mm depth was according to texture estimated by Bemlab as 66.9 and 73.8 mm m^{-1} for the open and netted orchard sections, respectively. This is comparable and slightly higher than the 67.7 and 68.9 mm m^{-1} estimated from soil texture according to Saxton et al. (1986) for the respective soils.

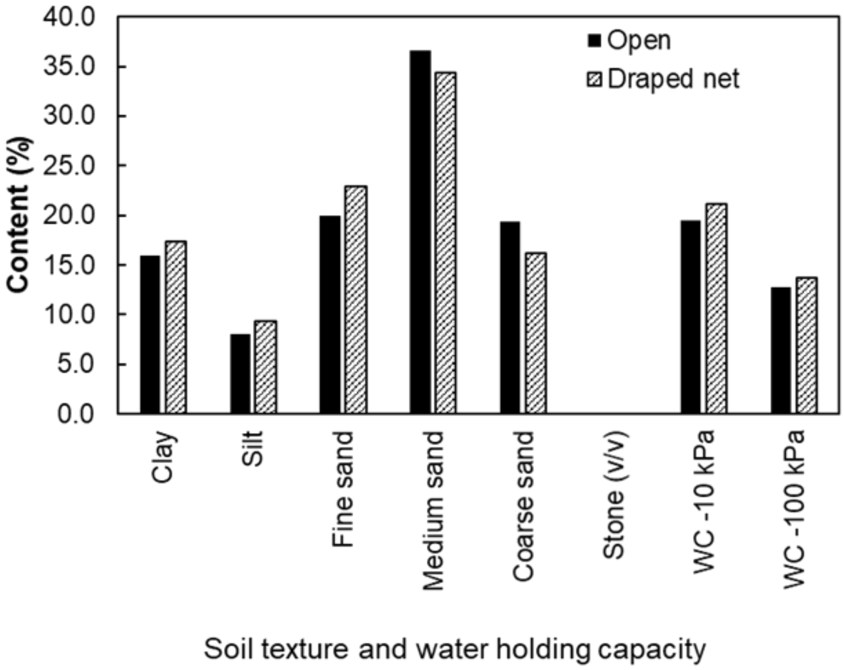


Figure 110 Soil particle size distribution and water content (WC) at -10 kPa and -100 kPa for the open (control) and netted areas in the 'Golden Delicious' orchard at Southfield in 2020-2021. Soils were sampled in the tree row and data averages represent the soil profile up to a 1.2 m depth.

Bulk density ranged between 1.52 and 1.67 in the tree row, 1.41 and 1.77 in the tractor track and 1.47 and 1.73 g cm^{-3} in the cover crop area (Figure 111). Although the profile bulk density on average (±standard deviation) tended to be higher in the open (1.64±0.052 g cm^{-3}) compared to the draped net area (1.55 ±0.087 g cm^{-3}) it was not significantly different. It also did not differ significantly for the open and draped net treatments for the tree row (1.63± 0.026 vs. 1.57±0.063 g cm^{-3}), tractor track (1.64±0.027 vs. 1.55±0.136 g cm^{-3}) and cover crop (1.64±0.09 vs. 1.52±0.05 g cm^{-3}) areas, respectively.

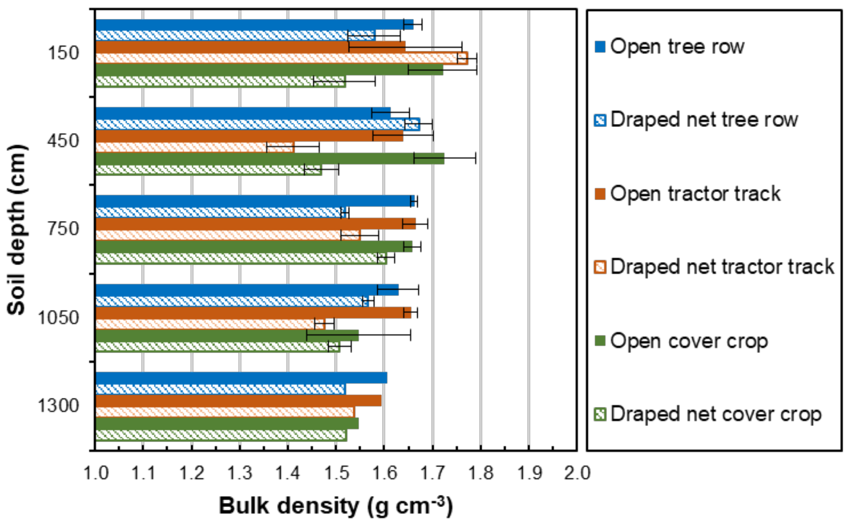


Figure 111 Soil bulk density and standard deviation (SD) for different soil depth increments of the soils sampled in the tree row, tractor row and cover crop area in rows adjacent to open (Control) and draped net soil water balance installations at the 'Golden Delicious' orchard at Southfield.

5.2.2.2 Soil water content dynamics and irrigation

Accurate soil water content information is a prerequisite to compare soil water content for different treatments. An *in situ* calibration was obtained for the CS650 sensors at the 150 mm depth for the tree row, tractor track and cover crop area, respectively, by pooling data of all four soil water balance installations (Appendix F, Figure 144). Comparison of volumetric soil water content calculated from the CS650 dielectric permittivity (K_a) using the manufacturer's calibration and actual soil water content at comparable K_a values indicated that the former underestimated the volumetric soil water content for the tree row and cover crop area at K_a values of less than about eight (Figure 144 & Figure 144). The manufacturer calibration furthermore tended to slightly overestimate the volumetric soil water content for all the orchard areas for K_a values of more than about ten. Comparison of volumetric soil water content calculated from the CS616 period using the manufacturer's calibration and actual soil water content at comparable CS616 periods for soil depths greater than 150 mm indicated that the former in general underestimated the volumetric soil water content for the control treatment (Figure 145a). It compared fairly well to actual soil water content for the draped net treatment except for a slight overestimation of soil water content at the wet end (Figure 145b).

The *CS616 in situ calibration* statistics for sensors indicated that the simple regressions between gravimetrically determined volumetric soil water content and K_a or CS616 period were all highly statistically significant ($p<0.0001$) and that the calibrations obtained accuracy equal to or better than the 2.5% indicated by the manufacturer. The error of the estimate for the sensors at soil depths exceeding 0.15 m was 1.9% and 2.4% at the control and draped net treatments, respectively. The error of the estimate for the sensors at the 150 mm depth in the tree row, tractor track and cover crop was 1.8, 1.3 and 2%, respectively. Outliers removed were attributed to variation in the spatial distribution of soil water along the length of the sensor prongs and of the sampled area vs sensor location. Soil water retention curves are required to interpret the soil water deficit levels the trees were subjected to. Soil water retention curves for the control and draped net treatments at 300 mm, 600 mm and 900 mm depths were obtained, but require further refinement (data not shown). The volumetric water content at -100 kPa supplied by Bemlab will therefore be used instead to indicate the relative levels of water deficit.

The approach followed to describe the soil water dynamics is to firstly compare volumetric soil water content (VWC) for the tree row, tractor track and cover crop areas for the control and draped net treatments, respectively. Secondly, soil water dynamics per depth for each treatment is discussed and thirdly, volumetric soil water content per treatment is compared between treatments. The VWC for both treatments decreased from the start of the season after 14.4 mm rain occurred on 9 October since a period of 26 days without irrigation or significant rainfall followed (Figure 112). This resulted in a steep decrease in VWC from 12 October until about 26 October, after which it decreased more gradually until 5 November when irrigation scheduling started.

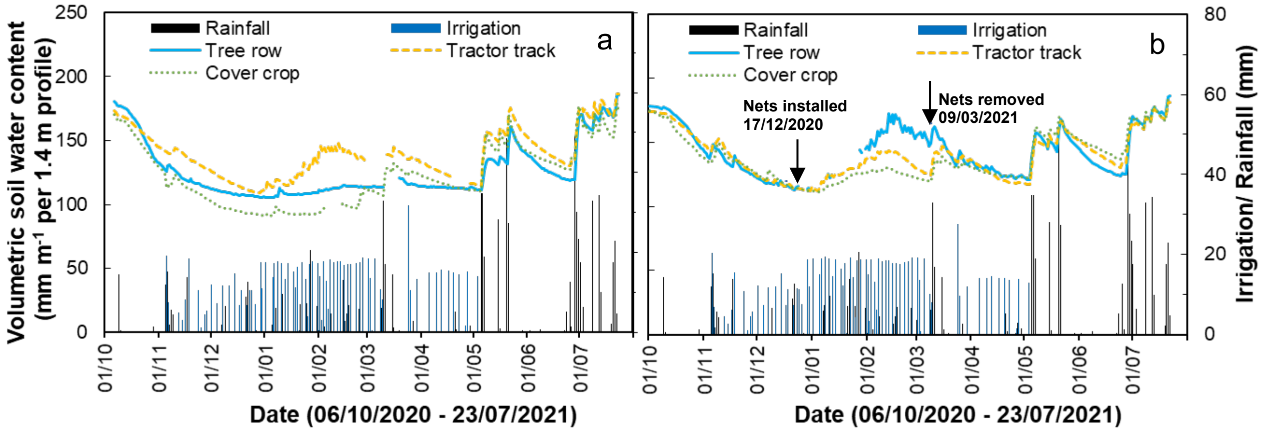


Figure 112 Comparison of volumetric soil water content for the tree row, tractor track and cover crop areas for the (a) open and (b) draped net sections of the orchard at Southfield from 6 October until 23 July 2021. Volumetric soil water content is based on in situ calibration.

At the beginning of the season, for the control treatment, the VWC in the tree row and cover crop area decreased initially at comparable rates, whereas water loss from the tractor track was less (Figure 112a). The downward trend in VWC tended to level off from 4 November but continued until about the end of December after which application of more irrigation increased the water status in the control treatment slightly. There was no apparent effect of nets installed during the period of 17-24 December 2020 on the VWC of the control treatment. Increased irrigation amounts appeared to have caused accumulation of water especially in the tractor track, which continuously displayed the highest VWC of all the orchard areas from 25 October until the end of the season. The VWC in the cover crop area increased gradually from the end of January, while the soil water status in the tree row remained low throughout the season until significant rainfall improved the soil water status from 5 May until the end of the season.

In the draped net treatment the VWC for the tree row and tractor track decreased at a comparable rate until end December (Figure 112b). The VWC for the cover crop area initially decreased at a faster rate than the tree row and tractor track until 5 November, but had similar VWC to the other areas until end December. Unfortunately a paucity of data prevented comparison of trends for the period directly after installation of the nets. However, it is clear that a combination of net and increased irrigation had a positive effect on the soil water status of the draped net treatment from the beginning of January as it tended to increase until mid-February. The VWC increased to a greater degree in the tree row than in the tractor track, and in the tractor track more than in the cover crop. The VWC thereafter decreased until harvest on 9 March, most likely due to application of less irrigation at greater intervals (Table 30), after which 50 mm rainfall on 10-11 March improved the soil water status (Figure 112b). From mid-March until 4 May the VWC in all orchard areas decreased gradually after which several significant rainfall events replenished water in the soil profile towards the end of the season.

Table 30 Monthly mean amount per irrigation event (±standard error or SE), number and interval of irrigations applied to the control and fixed net treatments at the 'Golden Delicious' orchard, Southfield during 2020-2021. Irrigation applied is indicated as mm per full surface area.

Month	Irrigation amount (mm d^{-1})				Number (n)	Interval (d)
	Control		Draped net			
	Mean	SE	Mean	SE		
Nov	1.8	0.6	1.7	0.6	10	3.0
Dec	2.8	0.7	3.0	0.7	13	2.4
Jan	5.0	0.9	5.5	1.0	17	1.8
Feb	5.2	1.0	5.5	1.1	15	1.9
Mar	2.6	0.9	2.5	0.8	9	3.4
Apr	2.3	0.8	2.1	0.7	8	3.8
May	0.3	0.3	0.3	0.3	1	31.0

The profile VWC up to 1.4 m depth for the tree row of the control treatment was lower than that for the draped net treatment from 23 October until 25 May (Figure 112). The VWC for the tractor track of both treatments was comparable for most of the season, whereas the VWC of the cover crop area for the control treatment tended to be lower than for the draped net treatment throughout the season.

Application of increased irrigation amounts from end December until early February improved the VWC for the control treatment tree row gradually especially at depths greater than 450 mm (Figure 113a). The VWC increased much more prominently in the tractor track at all depths (Figure 113b), whereas increased irrigation had a limited effect on the cover crop area (Figure 113c).

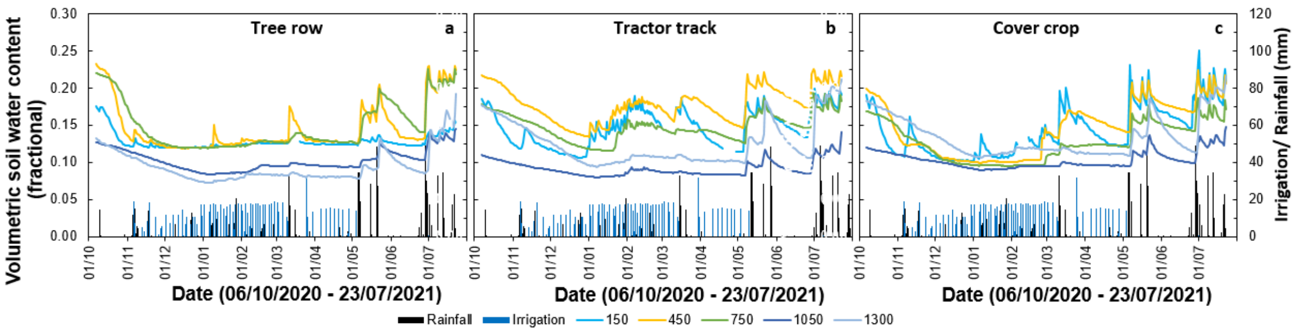


Figure 113 Soil water dynamics for the tree row (a), tractor track (b) and cover crop (c) in the open section of the orchard from October until July 2021. Volumetric soil water content for the different soil depths (mm) is based on in situ calibration and are for two replicates, except for the deepest soil layer in (a), which has only one replicate.

The presence of draped net in addition to increased irrigation resulted in a general upward trend in VWC at all depths for all orchard areas from end January until mid-February (Figure 114). There was a sharp decline in VWC at the 1.3 m depth for the tree row of the draped net treatment from middle November until end December, whereas VWC for the control treatment decreased at a much lower rate during this period (Figure 113a & Figure 114a).

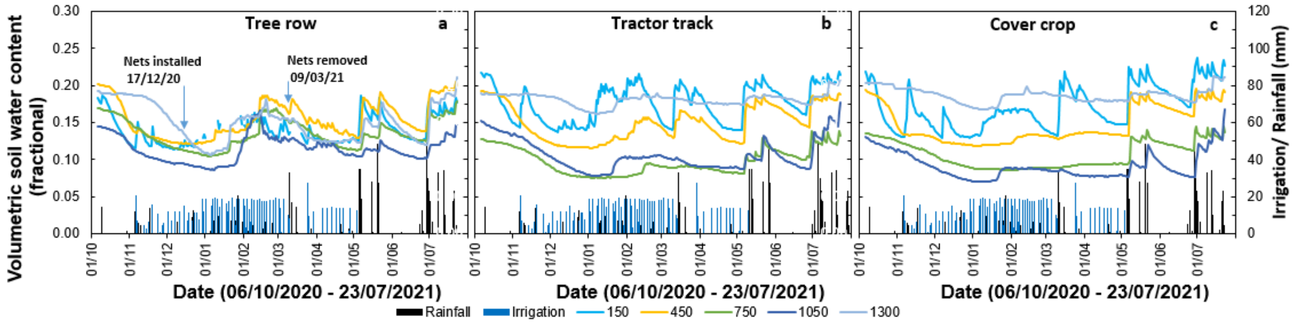


Figure 114 Soil water dynamics for the tree row (a), tractor track (b) and cover crop (c) in the draped net section of the orchard from October until July 2021. Volumetric soil water content for the different soil depths (mm) is based on in situ calibration and are for two replicates.

Comparison of the orchard VWC to a 1.4 m depth indicate that the control treatment was subjected for a longer period to soil water deficits exceeding -100 kPa than the draped net treatment (Figure 115). Limited availability of soil water at the control treatment may therefore have had a greater impact on tree water use and productivity compared to the draped net treatment.

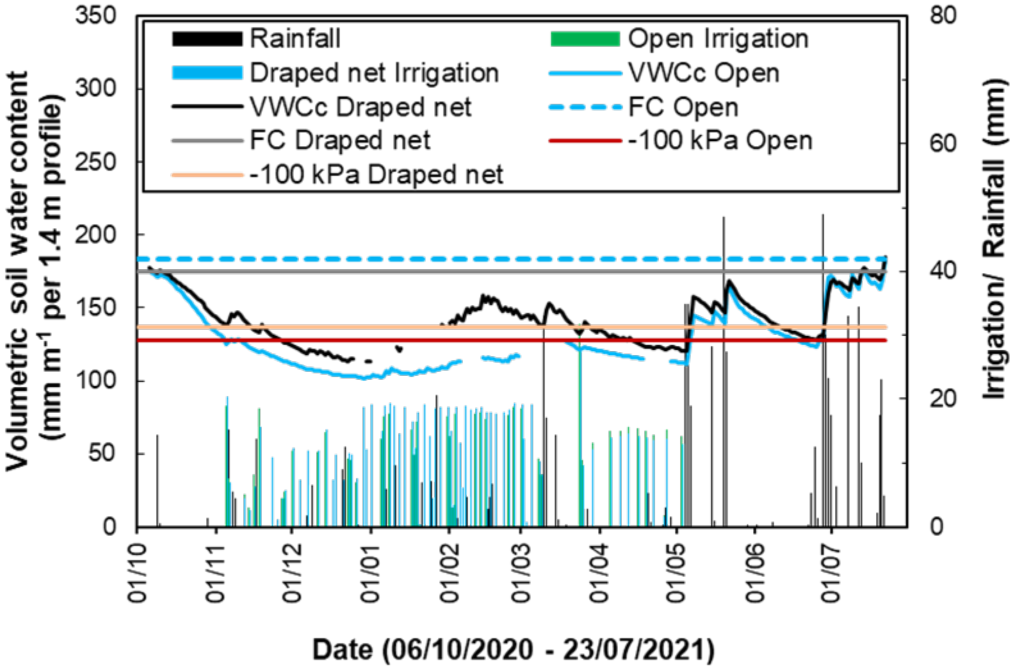


Figure 115 Soil water dynamics for the open and draped net sections from October 2020 until July 2021. Volumetric soil water content for the orchard was averaged taking the tree row, tractor track and cover crop surface area into account. The volumetric soil water content is based on in situ calibration and are for two replicates. The field capacity (FC) was determined in situ and the -100 kPa values are derived from soil particle size analysis (Bemlab).

5.3 VEGETATIVE GROWTH

5.3.1 Seasonal shoot growth

No significant differences between open (control) and net treatments were found for relative shoot growth rate in the 2019-2020 season for ‘Golden Delicious Reinders’ (Figure 116A) and in the 2020-2021 season for ‘Golden Delicious’ (Figure 116B, expressed as percentage shoot length change due to uneven shoot lengths at the start). Also, relative shoot growth (as a percentage of initial length) did not differ significantly between the five different crop load levels (Figure 116C), although there was a tendency for slightly stronger shoot growth at 60% and 80% crop load.

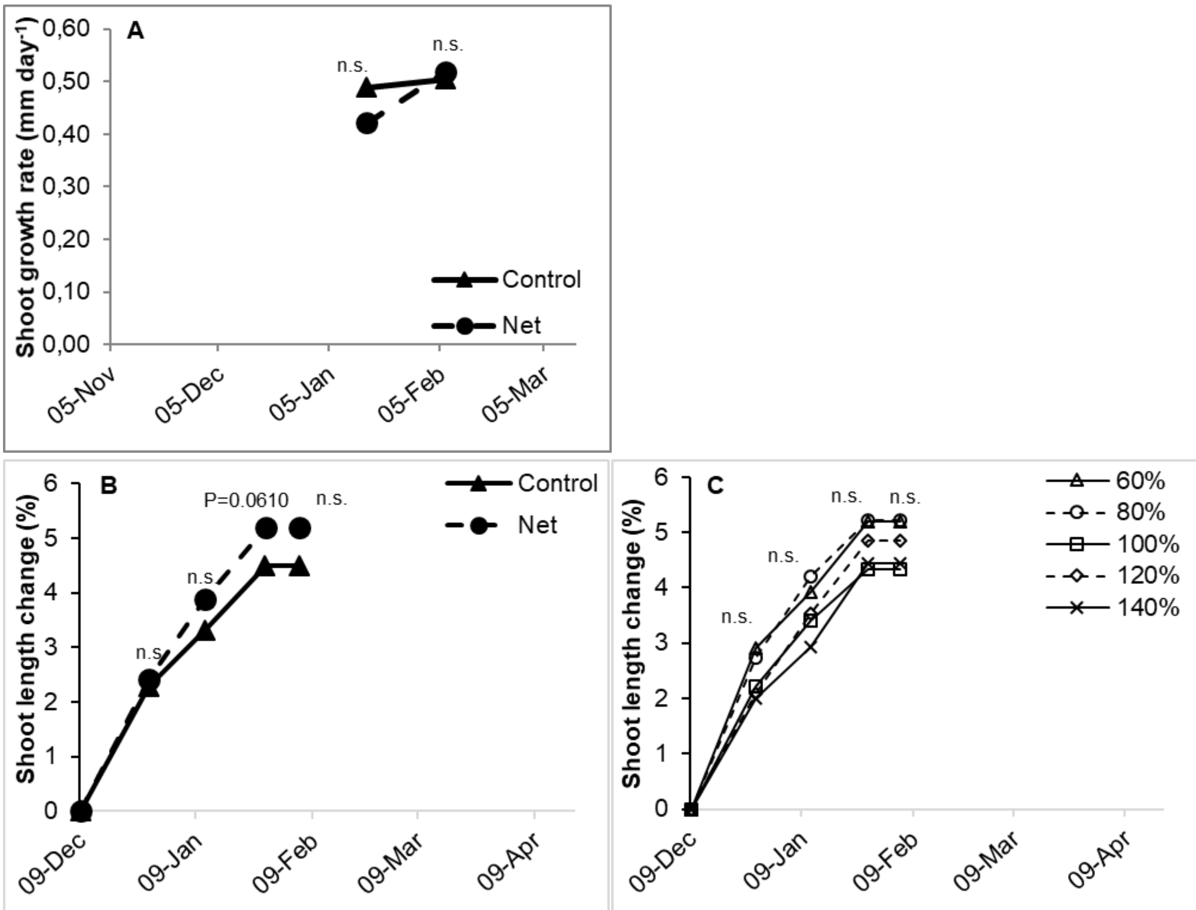


Figure 116. Relative shoot growth rate under the net and in the open of A) ‘Golden Delicious Reinders’ (2019-2020), and shoot percentage change in length of ‘Golden Delicious’ (2020/2021) in response to B) nets (crop load trial, net main effect) and C) crop load (crop load trial, crop load main effect). Crop load labels indicate the target yield as a percentage of the target commercial yield (100%). P-values indicate significance at the 5% level. N.S. = no significant differences.

5.4 WATER POTENTIAL, GAS EXCHANGE AND WUE

5.4.1 Leaf physiology – Paardekloof (KBV)

5.4.1.1 Water potential

Pre-dawn lead water potential ($\Psi_{pre\text{-}dawn}$) was relatively constant between mid-November 2019 and mid-March 2020 at Paardekloof (Figure 117a). A small but significant treatment difference was found on 12 February, with higher (less negative) values under the draped netting (netting still installed).). This was a hot and dry period.

In 2019-2020 at Southfield, values fluctuated strongly through the season (Figure 117b) and were generally lower compared to 2019-2020 (Paardekloof) from December onwards. No significant treatment differences were found while the draped netting was installed. After net removal and harvest, in mid-March to mid-April 2021, mean values were slightly but significantly higher (less negative) in the previously netted trees. This may be linked to the removal of all the fruit leading to a reduction in water use, or possibly due to the post-harvest irrigation regime.

Absolute levels of Ψ_{pd} on most measurement dates in both trials indicated that the trees were unlikely to have experienced any significant underlying water stress. The exception was in mid-April 2021, when low values of Ψ_{pd} were recorded for both treatments. This may be related to the cessation of irrigation at this time of the season, and before any meaningful rainfall could replenish the soil water. Values remained relatively low in May and June, but there were no treatment differences.

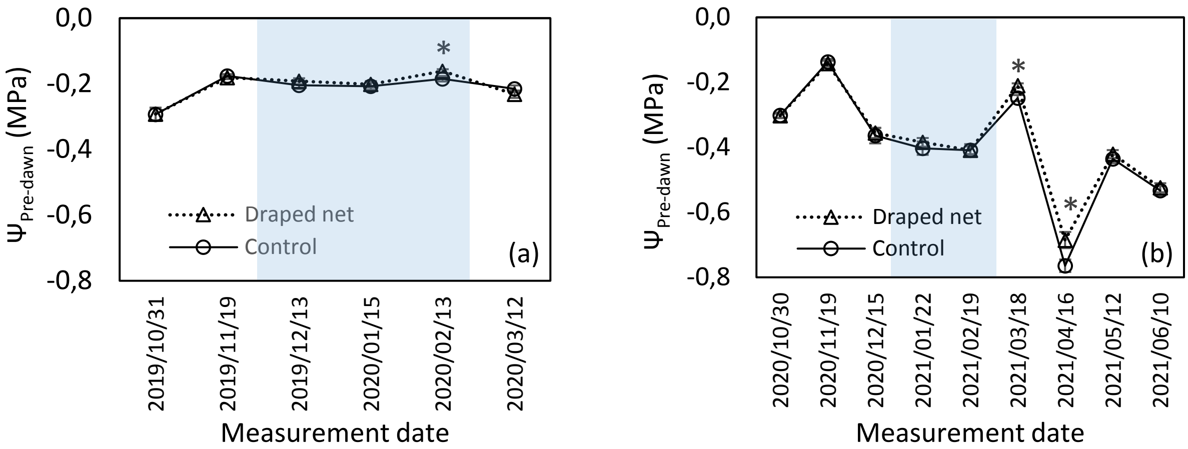


Figure 117 (a) Pre-dawn leaf water potential for draped netting and open (control) treatments in 2019-2020, and (b) 2020-2021. The blue shaded periods indicate the time that the draped netting was installed in the orchard.

Figure 118 presents the midday leaf xylem water potential through the season for the draped netting trials. In 2019-2020 (Figure 118a), midday Ψ_{xylem} decreased gradually through the season until mid-February, with a slight increase in mid-March after the harvest. A significantly higher Ψ_{xylem} was measured under the net on 13 December 2019, two weeks after net installation, but not thereafter. The “stress threshold” of Ψ_{xylem} < -1.2 MPa for full-bearing apple trees (Naor, 2014) was not reached in either treatment.

In 2020-2021 (Figure 118b), midday Ψ_{xylem} was significantly higher under draped netting throughout the period of net installation, and slightly elevated in these trees before net installation (mid-November 2020) and after net removal (mid-April). The “stress threshold” was broadly not exceeded on the measurement dates in October, November, February (only in the control treatment), March, May and June. However, Ψ_{xylem} was lower than -1.2 MPa during December, January and April (both treatments) and in February (control treatment). This indicates a high water use during the day with insufficient internal replenishment, particularly on 22 January.

One week after harvest, on 18 March, Ψ_{xylem} was higher in both treatments, possibly as a result of the removal of all the fruit leading to a reduction in water use. Higher Ψ_{xylem} in previously netted trees compared to open trees in April could be either attributed to a lasting effect of the netting on lowering the tree water use, e.g. through changes in canopy size, increased root water uptake capacity and/or hydraulic conductivity, or differences in irrigation volumes between the treatment rows. However, it could also be linked to the similar effect measured in November, and possibly point to initial differences in these or another factor between the trial trees.

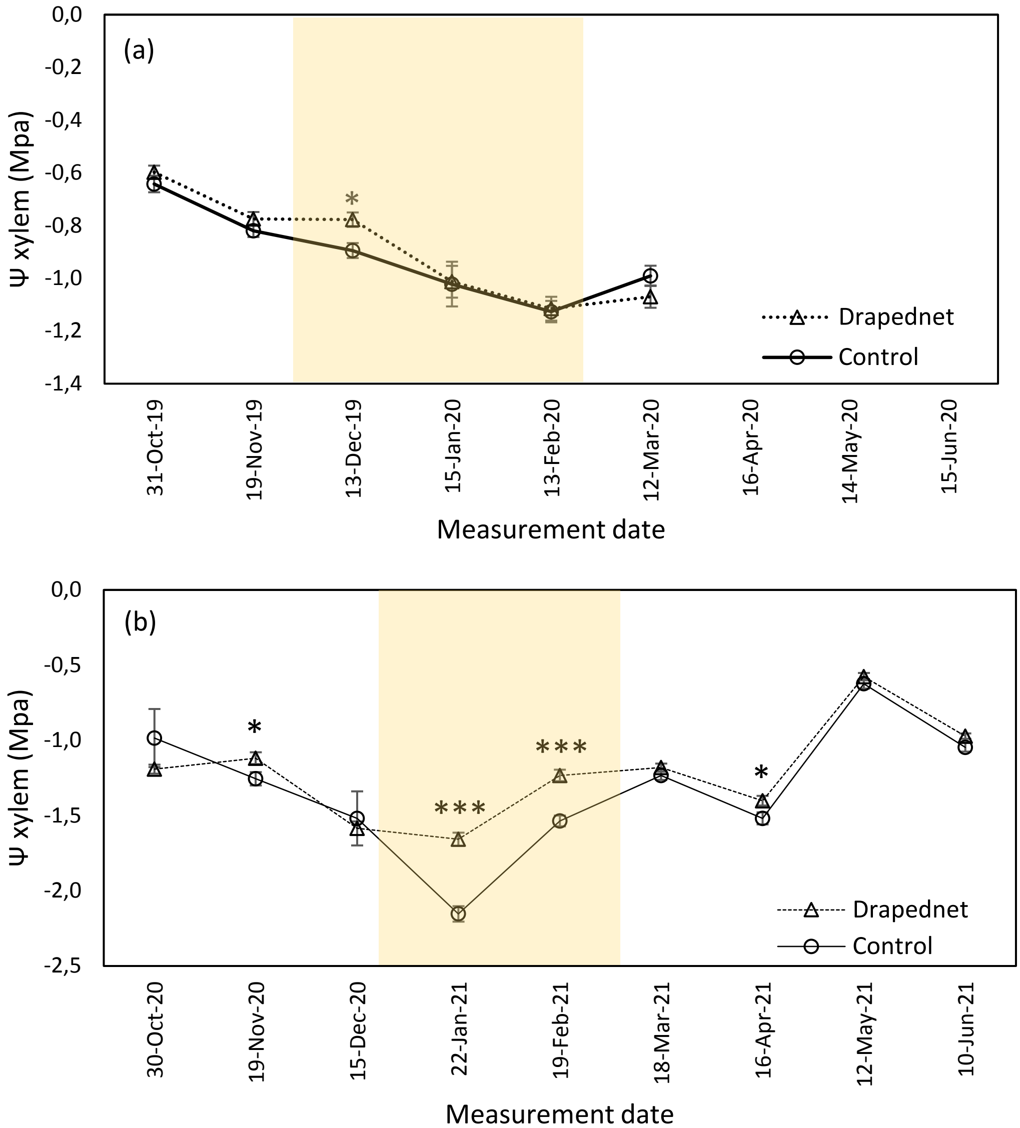


*Figure 118 Midday stem water potential (Ψ_{stem}) of (a) ‘Golden Delicious Reinders’ apple trees under black draped netting in 2019-2020, and (b) ‘Golden Delicious’ apple trees under draped netting in 2020-2021. Values are means ± standard error, and * = P<0.05, ** = P<0.01, *** = P<0.001 according to a T-test. The blue shaded periods indicate the time that the draped netting was installed in the orchard.*

5.4.1.2 Leaf gas exchange and WUE

Draped netting in 2019-2020 led to a slight but not significant reduction in A while the net was installed, and a significantly lower A just after net removal in mid-March 2020 (Figure 119a). On this day, g_s was also significantly lower in previously netted trees (Figure 119c). Since ambient solar radiation was tracked in the cuvette, this indicates the actual situation under the net during the course of the season. Transpiration rate (Figure 119e), WUE_{inst} (Figure 119g) and leaf surface temperature (Figure 119i) were not affected.

The following season (2020-2021), A, gs and E were all slightly but significantly higher in the net treatment trees, starting before the net was installed (Figure 119b, Figure 119d, Figure 119f). This response ended in late January 2021, except for a peak in g_s in May 2021 which was slightly higher for previously netted trees. WUE_{inst} was higher in the control treatment in October 2020 (Figure 119h), owing to a higher A in this treatment (not significant), but WUE_{inst} was lower in the control in April 2021 due to a higher E (not significant). There were no treatment differences for leaf temperature (Figure 119j).

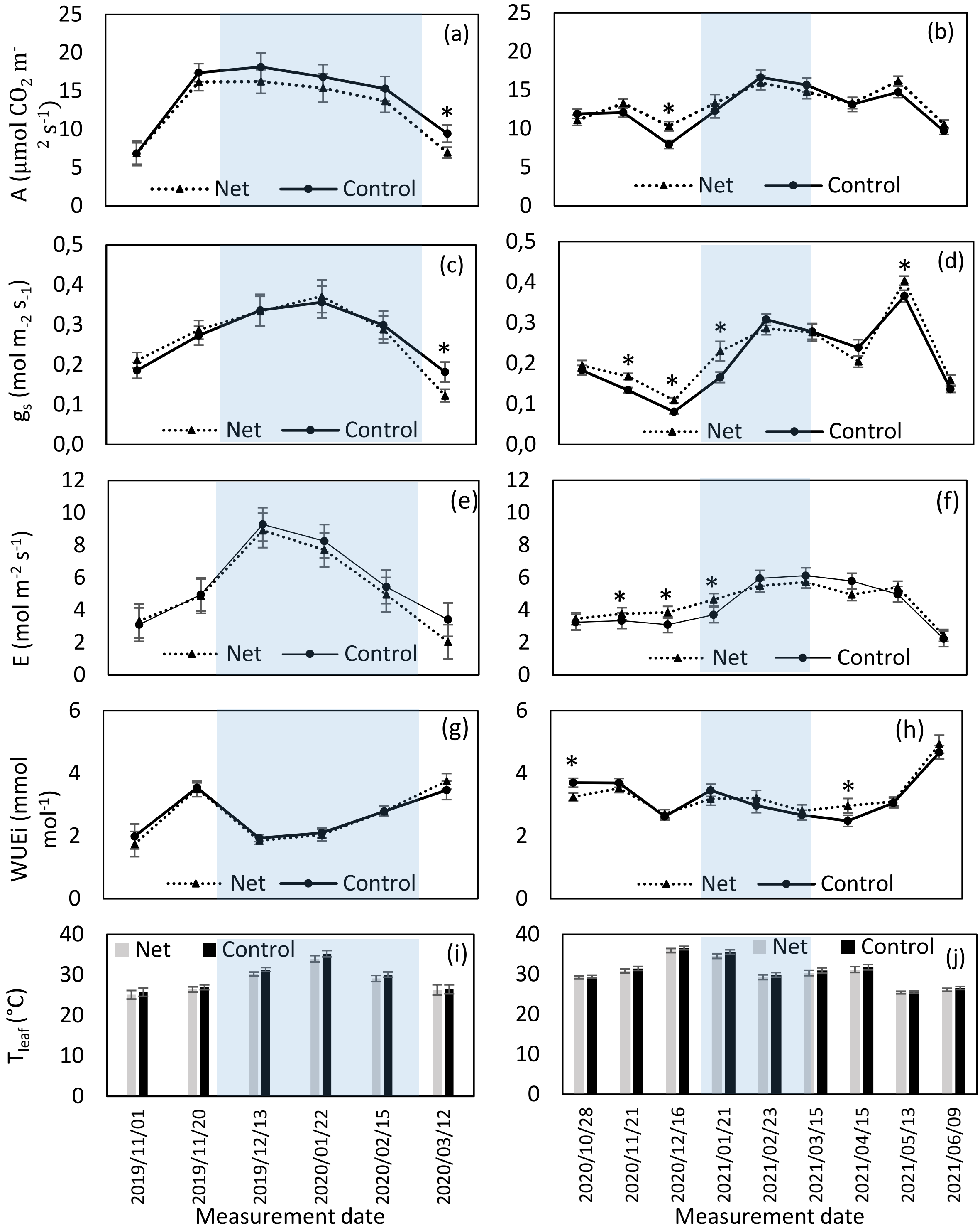


Figure 119 Monthly gas exchange responses of apple leaves to draped netting compared to open (control) treatments, including (a) and (b): net CO_2 assimilation rate (A); (c) and (d): stomatal conductance (g_s); (e) and (f): transpiration rate (E); (g) and (i): instantaneous water use efficiency (WUE_{inst}); and (i) and (j): leaf surface temperature (T_{leaf}). The left column of figures is for 2019-2020 ('Golden Delicious Reinders', KBV), and the right column is for 2020-2021 ('Golden Delicious', EGVV). Values are means with standard error bars. Means were separated by LSD at 5% when P≤0.05, according to repeated measures ANOVA. The blue shaded periods indicate the time that the draped netting was installed in the orchard.

5.5 TREE TRANSPIRATION DYNAMICS

5.5.1 Tree transpiration – Paardekloof (KBV)

The reduced atmospheric evaporative demand under draped nets affects water consumption by the trees, and here we provide estimates of potential water savings based on sap flow measurements at Paardekloof. In Figure 120, we present weekly data of both the total solar radiation (a) and transpiration (b). The weekly data shows less noise compared to daily and the effects of the draped nets on tree water use are much more evident (Figure 120b). Before the nets were installed the weekly total transpiration was almost similar between the control and draped nets treatments differing by between 1 and 4%. These differences are likely a result of tree size variations although the data were normalized to minimise these.

Installing the nets resulted in an average reduction in weekly total transpiration of about 8.5% over the period 27 November 2019 to 26 February 2020. This represents a much smaller reduction compared to the drop in radiation intensity or atmospheric evaporative demand discussed earlier. Possible explanation for the mild reduction in water use include the fact that the stomatal conductance was not significantly reduced by the draped nets (Figure 119). In some instances, this tended to be higher under the nets than in the open. Secondly, the reduction in key drivers of transpiration such as the VPD was very small (<0.1 kPa) under the nets, implying that high transpiration rates are probable perhaps at a lower rate than for the control trees. The difference in the radiation intensity between the two treatments was the main driver of the variation in water use as confirmed by Figure 121.

For the period 02 October 2019 to 30 June 2020, the total water consumption by the trees was 3850 m^3/ha compared to 3730 m^3/ha for the draped nets, representing a 3% difference. The small difference in the seasonal total water use is likely a result of tree size differences between the two treatments. Also, the water use values reported here are lower than those observed on the same cultivar in previous studies (Dzikiti et al., 2018a) due to the late start of the sap flow measurements owing to technical difficulties.

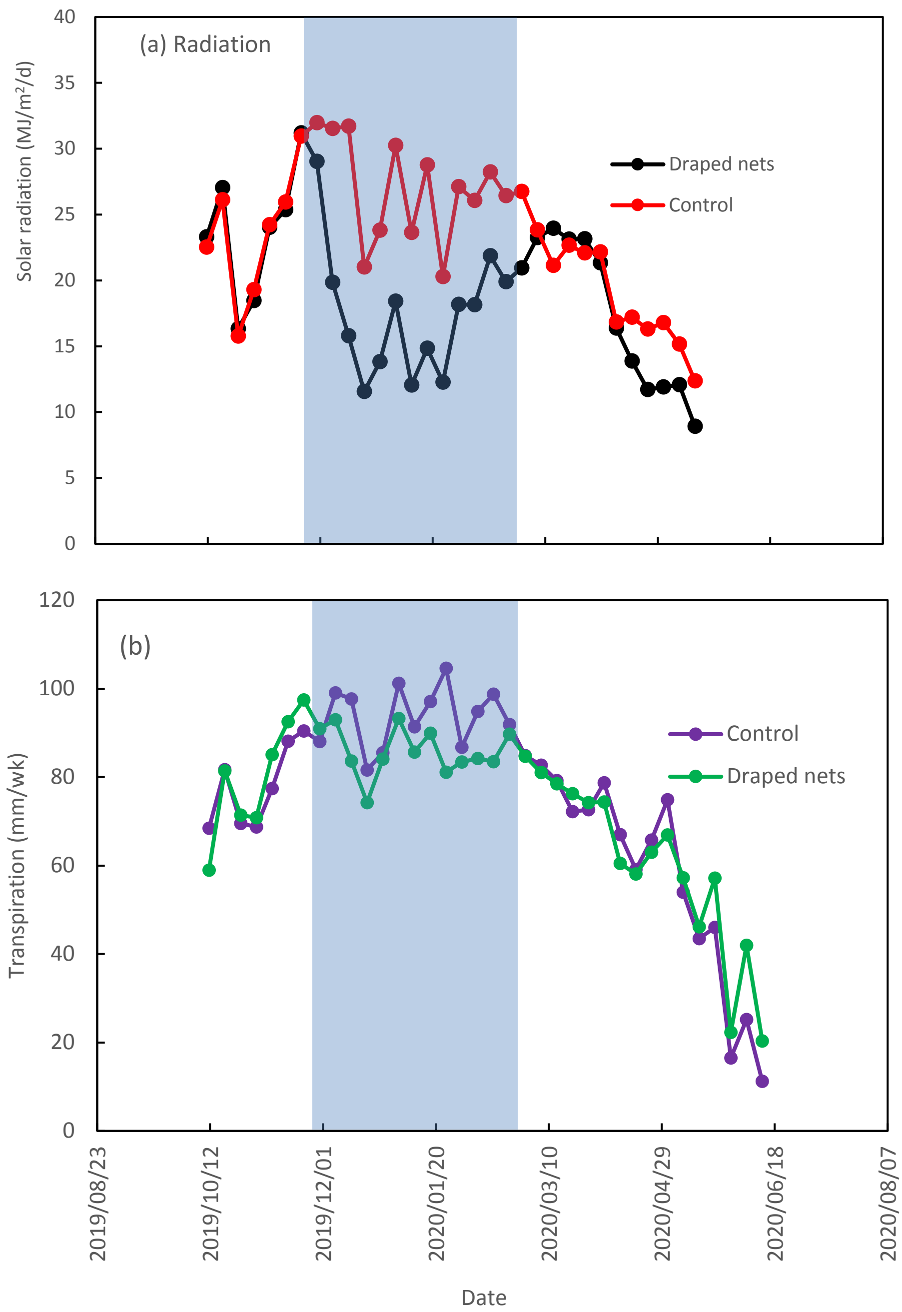


Figure 120 (a) Weekly average solar radiation, and (b) weekly total transpiration for the control and draped nets treatments at Paardekloof.

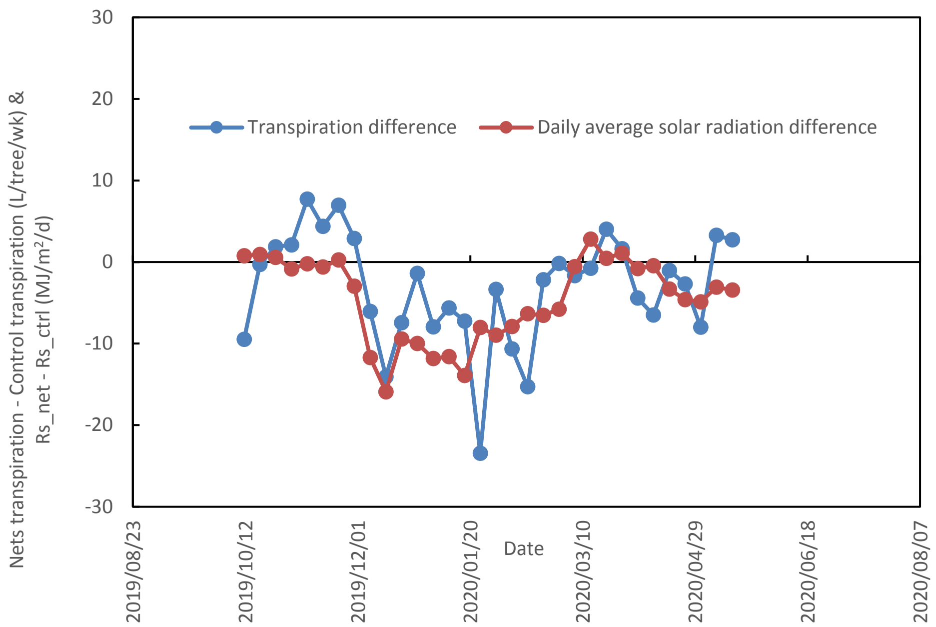


Figure 121 Comparison of the difference in daily solar radiation and daily transpiration under draped nets at Paardekloof.

5.5.2 Tree transpiration – Southfield (EGVV)

The daily transpiration dynamics for control and draped nets 'Golden Delicious' apple trees at Southfield for the 2020-2021 season are shown in Figure 122. Transpiration peaked at about 30.2 litres per tree per day for both treatments on 13 November 2020 prior to the installation of the nets. This water use rate agree with values reported for the same orchard during 2015-2016 by Dzikiti et al. (2018a). The nets were installed on 17 December 2020 and removed on 8-10 March 2021. The decline in transpiration over this period is evident in Figure 122. Before the draped nets were introduced, the differences in the water use between trees in the two treatments was about 3%, averaged over the period 01 October to 24 December 2020. When the draped nets were installed the transpiration under the nets dropped by about 8.3% averaged over the period 25 December 2020 to 07 March 2021. The order of magnitude of the decrease in tree transpiration under the draped nets is similar to that obtained at Paardekloof (~8.5%) on 'Golden Delicious Reinders'. The initial differences in water use before installation of the nets were a result of tree size differences.

Figure 123 shows the difference in water use over the season and the effect of the draped nets. After the nets were removed, the transpiration under the draped nets remained somewhat lower than for the control, possibly due to the acclimation of the trees to the lower light environment. It could also be that the control trees retained their leaves for longer compared to the netted treatment, leading to higher water use for the control. But further observations are needed to confirm this especially given that the same trend was not reported for Paardekloof.

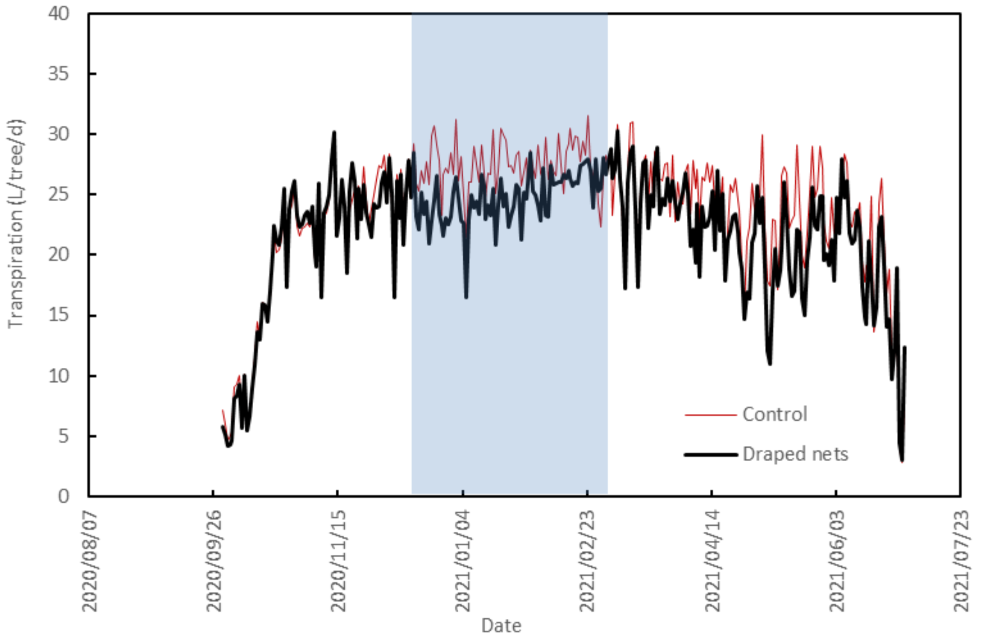


Figure 122 Comparison of the daily transpiration between the control and the draped nets treatment at Southfield farm, Villiersdorp.

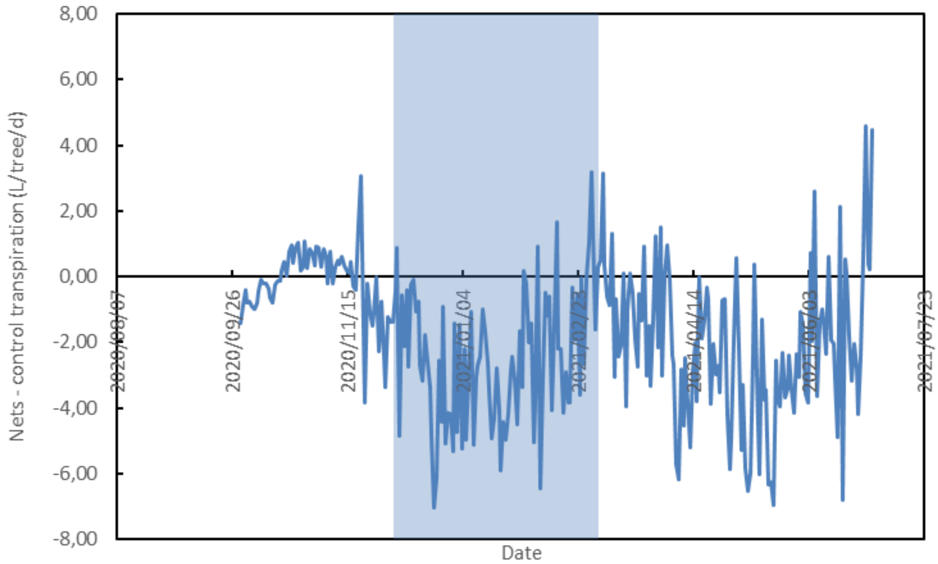


Figure 123 Difference in average tree transpiration for trees under draped nets and in the open (control).

5.6 ORCHARD EVAPOTRANSPIRATION AND WATER SAVING

5.6.1 Evapotranspiration – Paardekloof (KBV)

As in the case of 'Rosy Glow', the monthly averaged ET of the 'Golden Delicious Reinders' orchard followed the general trend of ET_o over the season (Figure 124). The monthly averaged ET tended to be higher for the control compared to the draped net treatment for the whole season. The control and draped net treatment ET appeared to be comparable during September and during the draped net period of December to February. However, the control treatment ET was higher compared to the draped net treatment ET in October, November and from March until June.

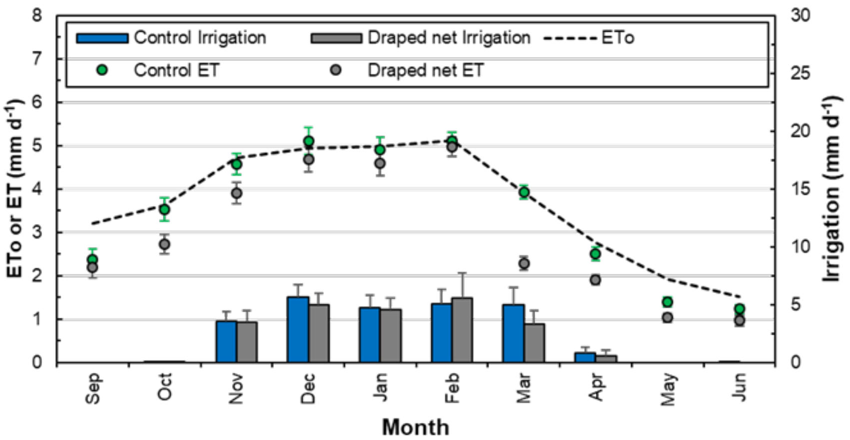


Figure 124. Monthly averaged Penman-Monteith reference evapotranspiration (ET_o), 'Golden Delicious Reinders' crop evapotranspiration (ET) and irrigation applied for trees in the open (Control) and below draped net at Paardekloof. Draped net trees were covered on 28/11/2019 and net removed on 26/02/2020. Error bars indicate the standard error for the monthly average.

The ET increased from c. 2.3 mm d^{-1} in September 2019 to a maximum of 5.1 mm d^{-1} and 5 mm d^{-1} in February 2020 for the control and draped net treatments, respectively (Figure 124). For the control treatment the ET decreased gradually from February to c. 1.1 mm d^{-1} in June 2020. However, for the draped net treatment the ET was during March and April reduced by c. 42% (1.7 mm d^{-1}) and 24% (0.6 mm d^{-1}), respectively, compared to the control treatment (Table 31). The largest difference in irrigation application between treatments occurred in March and April when the control received c. 33% more irrigation than the draped net treatment (Figure 124).

During the season the control treatment received 7512 m^3 ha^{-1} irrigation compared to 6797 m^3 ha^{-1} for the draped net treatment (i.e. c. 10% more) (Table 32). However, during the draped net period from 28 November 2019 until 26 February 2020 both treatments received similar amounts of irrigation (4793 and 4791 m^3 ha^{-1} for the control and draped net treatments, respectively). Seasonal ET (14 September 2019 until 30 June 2020) for the control treatment amounted to 10167 m^3 ha^{-1}, which was c.18% higher than the 8355 m^3 ha^{-1} ET determined for the draped net treatment. If only the period from October until 30 June is considered these amounts are 9819 m^3 ha^{-1} and 7990 m^3 ha^{-1} for the control and draped net treatments, respectively and the difference amounts to 19% (Table 32). For the draped net period the control treatment ET (4571 m^3 ha^{-1}) exceeded the draped net treatment ET (4246 m^3 ha^{-1}) by c. 7%. Closer inspection of data is necessary to clarify why the ET at the draped net treatment was lower compared to the control early in the season.

Table 31. Comparison of the total monthly and seasonal evapotranspiration for 'Golden Delicious Reinders' trees in the open and under draped net during the 2019-2020 growing season.

Month	Evapotranspiration						
	Control (m^3 ha^{-1})	Draped net 1.2 m (m^3 ha^{-1})	Draped net 1.4 m* (m^3 ha^{-1})	Difference 1.2 m (m^3 ha^{-1})	Difference 1.4 m* (m^3 ha^{-1})	Difference 1.2 m (%)	Difference 1.4 m* (%)
Oct	1093	785	793	308	300	28	27
Nov	1370	1144	1174	226	196	16	14
Dec	1581	1377	1404	204	177	13	11
Jan	1519	1363	1424	157	95	10	6
Feb	1484	1422	1442	61	41	4	3
Mar	1218	707	706	510	512	42	42
Apr	751	578	573	174	178	23	24
May	432	270	269	162	163	38	38
Jun	371	210	204	160	167	43	45
Oct-May	9448	7647	7786	1802	1662	19	18
Oct-Jun	9819	7857	7990	1962	1829	20	19

* Averaged for 1.2 and 1.4 m profiles (2 reps).

Table 32. Comparison of the total monthly and seasonal irrigation for 'Golden Delicious Reinders' trees in the open and under draped net during the 2019-2020 growing season.

Month	Irrigation			
	Control (m^3 ha^{-1})	Draped net (m^3 ha^{-1})	Difference (m^3 ha^{-1})	Difference %
Oct	0	1	-1	-133
Nov	1061	1038	23	2
Dec	1744	1536	209	12
Jan	1459	1417	42	3
Feb	1467	1611	-144	-10
Mar	1543	1038	505	33
Apr	237	156	81	34
May	0	0	0	0
Jun	1	0	1	100
Oct-May	7511	6797	714	10
Oct-Jun	7512	6797	716	10

5.6.2 Water saving – Paardekloof (KBV)

When the calculations were made for the leafy season (October to June) an ET-based water saving of 1829 m^3 ha^{-1} (with soil sensors at 1.4 m depth) or 1962 m^3 ha^{-1} (with soil sensors at 1.2 m depth) was found under the nets compared to the open (Table 33).

The ET-based water use efficiency estimate indicates a saving of about 16-17 m^3 ton^{-1} under the draped net compared to the control/open treatment. This is attributable to the reduction in ET combined with a small yield increase under the net.

The irrigation data suggests a water saving of around 715 m^3 ha^{-1} under the net compared to the open, and the irrigation productivity estimate showed a reduction of around 8 m^3 ton^{-1}.

Table 33. Total evapotranspiration (ET, m^3 ha^{-1}), water use efficiency based on ET (WP, m^3 ton^{-1}), irrigation applied (m^3 ha^{-1}), and irrigation productivity (IP, m^3 ton^{-1}) for 'Golden Delicious Reinders' trees in the open and under draped nets during the 2019-2020 growing season, and the difference (potential water "saving" – if positive; potential water "over-spending" – if negative). Values are shown for the fruit season when trees are in leaf (October to June) since the monitoring equipment was only installed in September.

	ET Control	**ET Draped Nets (1.2 m)**	**ET Draped Nets (1.4 m)**	**Difference (1.2 m)**	**Difference (1.4 m)**
October to June (m^3 ha^{-1})	9819	7857	7990	1962	1829
	WUE Control	**WUE Nets (1.2 m)**	**WUE Nets (1.4 m)**	**Difference (1.2 m)**	**Difference (1.4 m)**
October to June (m^3 ton^{-1})	68.8	51.9	52.8	16.9	16.1
	Irrigation Control	**Irrigation Nets**		**Difference**	
October to June (m^3 ha^{-1})	7512	6797		715	
	IP Control	**IP Nets**		**Difference (Control – Nets)**	
October to June (m^3 ton^{-1})	52.6	44.9		7.8	

5.6.3 Evapotranspiration – Southfield (EGVV)

The monthly averaged ET_o and crop ET for the 2019-2020 season are summarised in Figure 125. Monthly averaged ET_o increased from 4.9 and 5.1 mm d^{-1} in October and November 2020, respectively, to a maximum of 6.1 mm d^{-1} in January 2021. After this the ET_o gradually decreased to 5.5 mm d^{-1} in February and steeply towards May and June 2021 where it levelled off at 2.1 mm d^{-1}. The ET in general followed the ET_o trend over the season, but soil water status also may have affected the ET trends. Based on monthly averaged values, the daily ET of the control was at the beginning of the season almost 20% higher than in the draped net treatment (2.8±0.1 mm d^{-1}). From November though, the trend for the control ET dropped below that of the draped net treatment and remained lower for the rest of the season. The ET for the control increased almost linearly from 2 (±0.1) mm d^{-1} in November to a maximum of 5 (±0.2) mm d^{-1} in February, after which it decreased steeply to c. 2.5 (±0.3) mm d^{-1} in March and more gradually to April (2.3±0.2 mm d^{-1}) and May (1.9±0.1 mm d^{-1}), reaching a minimum of 1(±0.1) mm d^{-1} in June. The draped net ET increased from 2.7±0.2 mm d^{-1} in November to a maximum of 5.4±0.2 mm d^{-1} in January. The ET for the draped net treatment was 5.3 (±0.2) mm d^{-1} in February, after which it decreased less steeply than the control ET to reach 3.4 (±0.2) mm d^{-1} in March. The ET for April until June was comparable to that for the control.

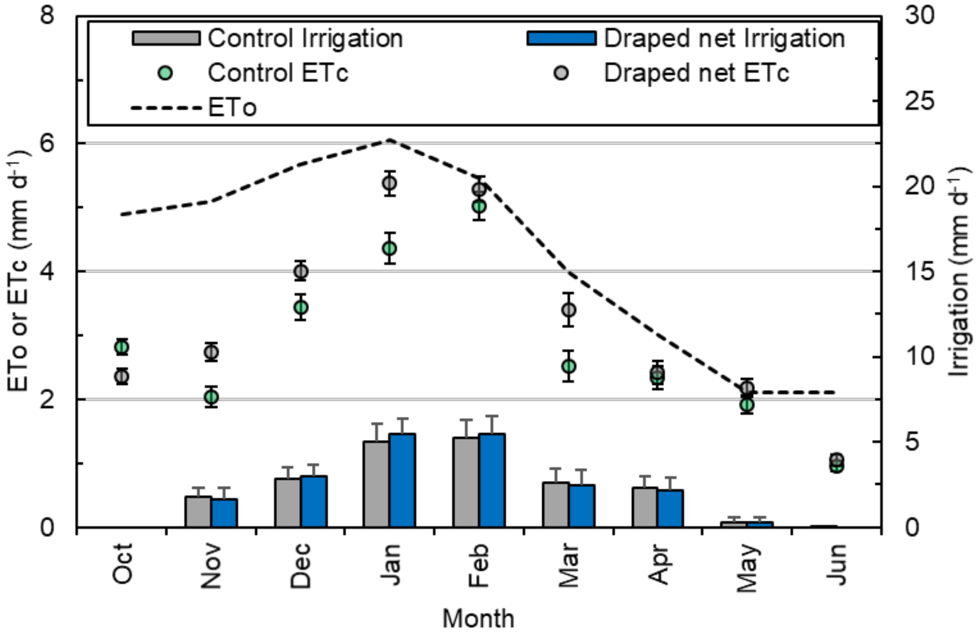


Figure 125. Monthly averaged Penman-Monteith reference evapotranspiration (ET_O), 'Golden Delicious' orchard evapotranspiration (ET) and irrigation applied in the open (Control) and below draped net at Southfield. Error bars indicate the standard error.

During November, December, January and March the ET in the control was 26, 14, 19 and 26%, respectively, lower compared to draped net treatment ET. For February and from April until June the control treatment and draped net treatment ET tended was comparable. The monthly total ET for the control was 10% more for October, but 35%, 17%, 23% and 35% less than ET below draped net during November, December, January and March, respectively (Table 34).

Table 34. Comparison of the total monthly and seasonal evapotranspiration for 'Golden Delicious Reinders' trees in the open and under draped net during the 2020-2021 growing season.

Month	Evapotranspiration			
	Control (m^3 ha^{-1})	Draped net (m^3 ha^{-1})	Difference (Control-Draped net) (m^3 ha^{-1})	Difference %
Oct	314	282	32	10,1
Nov	612	824	-212	-34,6
Dec	1067	1243	-176	-16,5
Jan	1354	1667	-314	-23,2
Feb	1407	1481	-74	-5,3
Mar	782	1055	-273	-34,9
Apr	703	727	-24	-3,4
May	593	674	-81	-13,6
Jun	289	314	-25	-8,8
Full Bloom* June	7121	8267	-1147	-16,1

*21 October 2020

Based on the monthly mean amount per irrigation event the treatments received similar irrigation (Table 30). Monthly averaged amounts of irrigation applied per day (±standard error) did not differ between treatments (Figure 125). Based on the seasonal total amounts (Table 35), the draped net orchard received a mere 2.3% more irrigation than the control (i.e. 6142 m^3 ha^{-1} for draped net compared to 6006 m^3 ha^{-1} for the control). The seasonal total ET from full bloom at 21 October 2020 until 30 June 2021 for the draped net orchard amounted to 8267 m^3 ha^{-1} compared to 7121 m^3 ha^{-1} for the control (Table 34). The draped net treatment unexpectedly had 16% more ET for the season compared to the control treatment. Greater availability of soil water in the draped net treatment compared to the control, especially in the tree row, may have sustained higher ET rates (Figure 113 & Figure 114).

Table 35. Comparison of the total monthly and seasonal irrigation for 'Golden Delicious' trees in the open and under draped net during the 2020-2021 growing season.

Month	**Irrigation**			
	Control	**Draped net**	**Difference**	**Difference**
	(m^3 ha^{-1})	**(m^3 ha^{-1})**	**(m^3 ha^{-1})**	**%**
Nov	528	500	28	5,4
Dec	880	931	-52	-5,9
Jan	1558	1692	-134	-8,6
Feb	1465	1531	-66	-4,5
Mar	801	768	33	4,1
Apr	684	637	47	6,8
May	90	82	8	8,4
Oct-May	6006	6142	-136	-2,3

Both treatments were subjected to levels of soil water depletion exceeding the -100 kPa level near the beginning of November until at least the end of December. It appears as if the draped net treatment though had from the middle of November still access to more water deep in the soil profile compared to that available for the control treatment, which may have sustained higher ET for a longer period. The control treatment had according to the soil water dynamics less soil water available deep in the soil profile compared to the draped net treatment.

The control soil water content in the tree row was for most of the season less than the -100 kPa level, which may explain the tendency for the control to have lower ET compared to the draped net treatment. Draped net combined with increased irrigation from end December managed to improve the soil water status much more compared to the control with similar increased irrigation, but without net.

5.6.4 Water 'saving' – Southfield (EGVV)

When the calculations were made for the leafy season (October to June) an ET-based water "over-spend" of 1146 m^3 ha^{-1} was found under the nets compared to the open (Table 36). The ET-based water use efficiency estimate indicates a very small (negligible) increase of around 1 m^3 ton^{-1} under the draped net compared to the control/open treatment. The irrigation data suggests an increase water use of around 136 m^3 ha^{-1} under the net compared to the open, and the irrigation productivity estimate showed a reduction of around 6 m^3 ton^{-1}.

Table 36. Total evapotranspiration (ET, m^3 ha^{-1}), water use efficiency based on ET (WP, m^3 ton^{-1}), irrigation applied (m^3 ha^{-1}), and irrigation productivity (IP, m^3 ton^{-1}) for 'Golden Delicious' trees in the open and under draped nets during the 2020/2021 growing season, and the difference (potential water "saving" – if positive; potential water "over-spending" – if negative). Values are shown for when trees are in leaf (October to June).

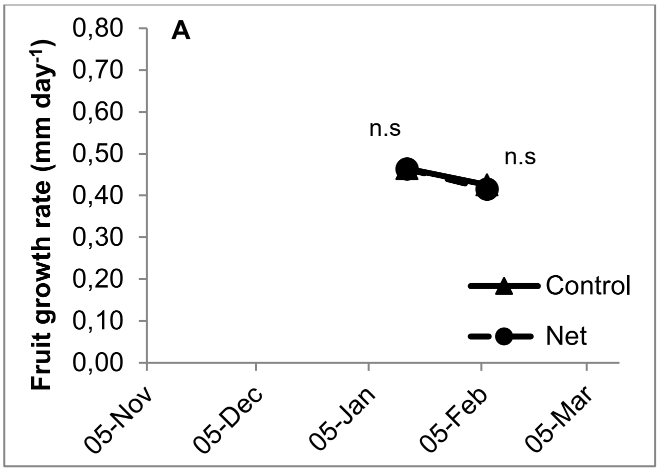
	ET Control	**ET Draped Nets**	**Difference (Control – Nets)**
October to June (m^3 ha^{-1})	7121	8267	-1146
	WUE Control	**WUE Nets**	**Difference (Control – Nets)**
October to June (m^3 ton^{-1})	69.7	71.0	-1.2
	Irrigation Control	**Irrigation Nets**	**Difference (Control – Nets)**
October to June (m^3 ha^{-1})	6006	6142	-136
	IP Control	**IP Nets**	**Difference (Control – Nets)**
July to June (m^3 ton^{-1})	58.8	52.7	+6.1

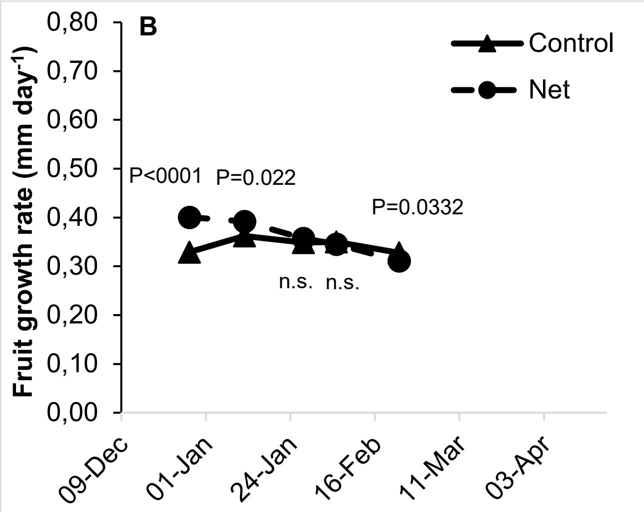
5.7 YIELD, FRUIT MATURITY AND FRUIT QUALITY

5.7.1 Fruit growth

In the 2019-2020 trial with 'Golden Delicious Reinders', no significant treatment differences were found for fruit size (23-25 mm, not shown) and relative fruit growth rate (Figure 126A) until early February when measurements ended.

For 'Golden Delicious' (2020-2021), initial fruit diameter (49 DAFB) was similar across all treatments (32-35 mm) (net/control: $P = 0.1034$; crop load: $P = 0.2398$). At the final date (124 DAFB), there was no significant difference in fruit diameter between the net/control treatments (56-57 mm) ($P=0.6685$), despite a higher initial relative fruit growth rate (Figure 126B). RGR was significantly higher under the lower crop loads (60% and 80% from January onwards compared to the 120% and 140% treatments (Figure 126C). No significant interactions between net/control and crop load treatments were found.





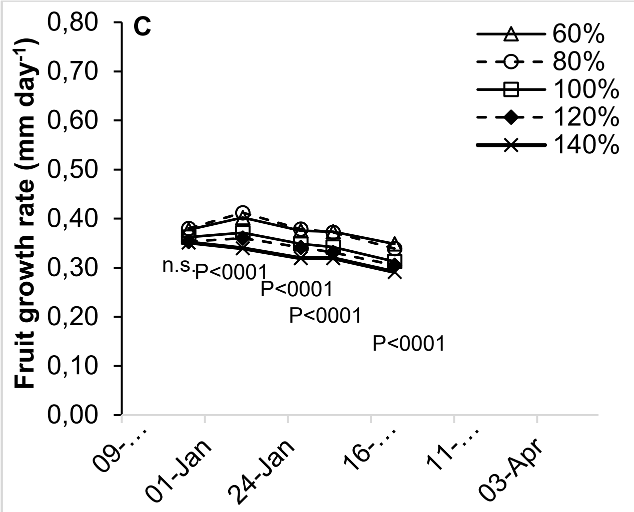


Figure 126 Fruit relative growth rate under draped netting and in the open of A) 'Golden Delicious Reinders' (2019-2020), B) 'Golden Delicious' (2020/2021, net/control main effect), and C) 'Golden Delicious' (2020/2021, crop load main effect).

5.7.2 Yield, fruit maturity and fruit quality

Yield and fruit number per tree, as well as mean fruit diameter and mass, for the ten trial trees per treatment, were not affected by the draped netting in both trials (Table 37, Figure 128). The variance in the data was high in both years. The yield efficiency was significantly higher in the control in 2020. Data provided by the farm for 2020 ('Golden Delicious Reinders') indicated a higher yield in the four rows under draped netting (151 t ha^{-1}) compared to the open (143 t ha^{-1}), with mean fruit mass of 130 g and 144 g, respectively (Table 38). It should be noted that the yields in both treatments were exceptionally high in 2020. The lack of fruit mass differences between treatments in the laboratory sample fruit could be a result of sampling. However, the fruit size distribution provided by the pack house (Figure 127) clearly showed a higher proportion of fruit up to count 165 (fruit size <68 mm) in fruit harvested under the net, and a lower proportion of larger fruit under the net, especially in counts 120 and 110. Data was not available in 2021. Pack house data was not available for the 2021 harvest.

Table 37 Yield, fruit number per tree, yield efficiency, fruit diameter, and individual fruit mass for the draped net and control treatments. Main trial results (for ten trial trees) of 'Golden Delicious' are shown. Means followed by the same lowercase letter were not significantly different at the 5% level according to Fisher's LSD test.

Treatment	**Yield (t ha^{-1})**	**Fruit number**	**Yield efficiency (kg cm^{-2} TCA)**	**Fruit mass (g)**	**Fruit diameter (mm)**
		'Golden Delicious Reinders' (2020)			
Net	132.1 ns	794 ns	0.27 b	142.4 ns	67.7 ns
Control	151.7	836	0.32 a	142.4	67.7
P-value	0.1404	0.6135	0.0298	0.9929	0.9401
		'Golden Delicious' (2021)			
Net	116.5 ns	1120 ns	0.42 ns	83.4 ns	59.0 ns
Control	102.1	902	0.45	90.5	60.4
P-value	0.3346	0.1021	0.5337	0.1561	0.2525

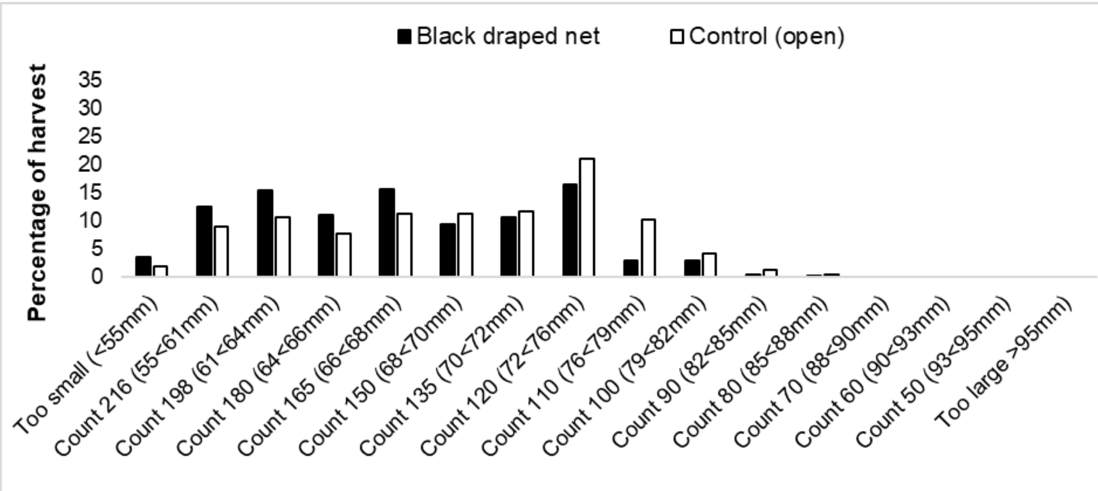


Figure 127 Fruit size distribution of the full harvest of 'Golden Delicious Reinders' under draped netting in 2019-2020. Data was provided by the pack house.

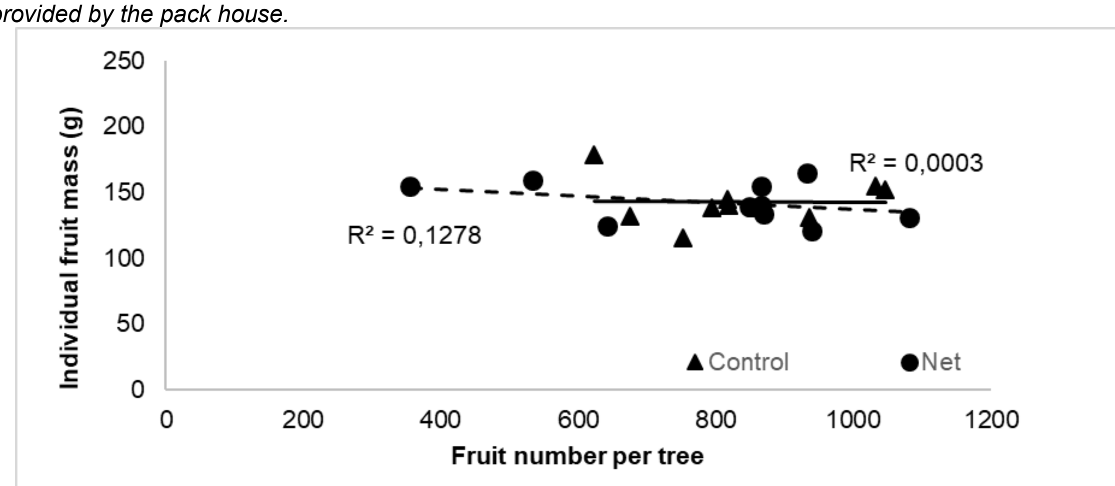


Figure 128. Relationships between mean individual fruit mass and fruit number per tree for the draped net and control treatments in 2019-2020.

Table 38 Pack house data for yield, individual fruit mass, other key fruit quality criteria, and packout percentage for the different class grades for 'Golden Delicious Reinders' apples grown under black draped netting in 2019-2020, compared to the open (control).

Variable	**Net**	**Control**
Yield (t ha^{-1})	151	143
Individual fruit mass (g)	130	144
Green fruit (%)	77	74
Sunburn (%)	1.9	4.2
Hail damage (%)	2.0	6.2
Class 1	20	21
Class 2	77	74
Class 3	3	5

Fruit quality and maturity under the two treatments are presented in Table 39 to Table 41. Background colour was slightly greener in the net treatment in 2021 (Table 39). Netting had no effect on retiform or stem-end russet. In both seasons, the number of healthy viable seeds was not significantly reduced under the netting compared to the control, although the number was lower.

In both draped net trials, fruit firmness was significantly decreased on both the sun-exposed and shaded cheeks (Table 40). Percentage starch breakdown was strongly advanced under the net in 2021 but not in 2020, and TSS was significantly lower under netting in both trials. The concentration of malic acid was not affected by the netting treatment.

Sunburn damage was very significantly reduced by the netting in both seasons, but particularly in 2021 (Table 41). A low level of sunburn (mostly Class 1, still marketable) was seen in the net treatment, whereas the control treatment had fruit with more serious sunburn, in Class 2, Class 3 and up to Class 8.

A summary of significant differences in fruit maturity and quality of 'Golden Delicious Reinders' (2019-2020) and 'Golden Delicious' (2020-2021) apples grown under black draped netting and in the open at this site is provided in Table 42. The positive impacts on yield, green (ground) colour, sunburn damage and hail damage are likely to be of greatest commercial value. Care should be taken with the timing of harvest since there were indications of advanced maturity development under the draped net.

Table 39 Fruit background colour, retiform russet, stem-end russet and the number of viable seeds for the net and control treatments. Main trial results (for ten trial trees) of 'Golden Delicious' are shown. Means followed by the same lowercase letter were not significantly different at the 5% level according to Fisher's LSD test.

Trt	Background colour (chart)	Russet retiform (chart)	Russet stem-end (chart)	Seed count
		'Golden Delicious Reinders' (2020)		
Net	2.08 ns	0.02 ns	3.29 ns	6.08 ns
Control	2.18	0.10	2.76	6.51
P-value	0.0744	0.0706	0.0988	0.2134
		'Golden Delicious' (2021)		
Net	1.42 b	0.03 ns	2.80 ns	3.88 ns
Control	1.54 a	0.06	2.93	4.33
P-value	0.0043	0.6218	0.6072	0.0863

Table 40 Fruit firmness of sun and shade exposed sides, percentage starch breakdown, total soluble solids (TSS) concentration and malic acid concentration for the net and control treatments. Main trial results (for ten trial trees) of 'Golden Delicious' are shown. Means followed by the same lowercase letter were not significantly different at the 5% level according to Fisher's LSD test.

Treatment	Firmness – sun (kg)	Firmness – shade (kg)	Starch breakdown (%)	TSS (%)	Malic acid (g $100g^{-1}$)
		'Golden Delicious Reinders' (2020)			
Net	7.09 b	7.08 b	55.8 ns	10.1 b	0.44 ns
Control	7.25 a	7.28 a	52.4	10.8 a	0.42
P-value	0.0341	0.0112	0.4253	0.0217	0.3643
		'Golden Delicious' (2021)			
Net	7.84 b	7.84 b	50.5 a	12.1 b	0.42 ns
Control	8.16 a	8.23 a	24.4 b	13.8 a	0.48
P-value	0.0134	0.0069	<0.0001	<0.0001	0.0550

Table 41 Sunburn incidence, sunburn score (according to a colour chart), and the proportion of fruit in each sunburn class for the net and control treatments. C0 = no sunburn, while C1-C3 are categories for increasing severity of sunburn. Means followed by the same lowercase letter were not significantly different at the 5% level according to Fisher's LSD test.

Treatment	Sunburn incidence (%)	Sunburn score (Chart)	Sunburn C0 (%)	Sunburn C1 (%)	Sunburn C2 (%)	Sunburn C3 (%) & higher
			'Golden Delicious Reinders' (2020)			
Net	3.5 b	0.04 b	96.5 a	3.0 ns	0.5 b	0.0 b
Control	23.0 a	0.78 a	77.0 b	7.0	5.0 a	11.0
P-value	0.0006	0.0002	0.0006	0.0971	0.0104	*
			'Golden Delicious' (2021)			
Net	6.5 b	0.08 b	93.5 a	5.0 b	1.5 b	0.0 b
Control	50.5 a	0.76 a	49.5 b	29.0 a	18.0 a	3.5
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	**

* Class C3 (P = 0.0077); Class C4 (P=0.1501); Class C5 (P=0.1211); Class C6 (P=0.3306); Class C7 (P=0.0872); Class C8 (P = 0.0077)

** Class C3 (P<0.0001); Class C4 (P=0.1701); Class C5 (P=0.4805);

Table 42 Summary of commercial significance of changes in fruit maturity and quality of 'Golden Delicious Reinders' (2019-2020) and 'Golden Delicious' (2020-2021) apples sampled from the netted orchard relative to apples sampled from the open orchard. The likely commercial significance of the changes is indicated. (+) = positive commercial impact; (-) = negative commercial impact. n/a = not available. An "-" indicates that values were not statistically significantly different for the sample assessment. "Orchard" indicates a result only for the full harvest.

Parameter	**Commercial significance**	
	2019-2020	**2020-2021**
Yield	Some significance (+) (orchard)	-
Individual fruit mass	Some significance (-) (orchard)	-
Perc. fruit delivered to pack house (i.e. lower orchard cull)	High significance (+) (orchard)	n/a
Ground colour – greener	Some significance (+) (orchard)	Some significance (+)
Firmness – lower	Not significant (-) (but could require harvest adjustments)	Not significant (-) (but could require harvest adjustments)
% Starch breakdown advanced	-	High significance (-) (will require harvest adjustments)
TSS – lower	Not significant (-) (but could require harvest adjustments)	Not significant (-) (but could require harvest adjustments)
Viable seed count	-	- (but trend to lower count)
Sunburn – lower	High significance (+)	High significance (+)
Hail damage – lower	High significance (+)	n/a
Organic acid concentration	-	- (but trend to lower conc.)

5.8 WATER PRODUCTIVITY

5.8.1 Water productivity – Paardekloof (KBV)

5.8.1.1. Seasonal transpiration and evapotranspiration

The daily maximum transpiration of the trees in the open (control) was around 22.4 L $tree^{-1}$ day^{-1} compared to 17.1 L $tree^{-1}$ day^{-1} under the net (Table 43). The average daily transpiration per tree for the whole period was 13.0 and 11.2 L $tree^{-1}$ day^{-1} for the control and net treatments, respectively. An average tree under the net transpired 2 822 litres over the season compared to 3 264 litres in the open. Thus, on average, each tree in the open transpired about 442 litres more than under the net. Tree density in the orchard was 1428 trees per hectare. Thus, potential water savings as a result of transpiration reductions in all trees in one hectare was thus estimated at around 631 000 L ha^{-1} over the season.

Table 43. Daily and total seasonal transpiration and seasonal evapotranspiration in the control and draped net treatments at Paardekloof in 2019-2020.

Parameter	Mean T (L day^{-1})		Mean T (mm day^{-1})	
	Open	Draped Net	Open	Draped Net
Daily maximum	22.4	17.1	3.2	2.4
Daily average	13.0	11.2	1.9	1.6
Total seasonal	3264 (L $tree^{-1}$)	2822 (L $tree^{-1}$)	466.0 (mm)	402.9 (mm)
Parameter			**Total ET (mm)**	
			Open	**Netted**
Total seasonal			1016.7	835.5

Converting the tree sap flow into equivalent depth units, transpiration under the draped net peaked at 2.4 mm d^{-1} compared to 3.2 mm d^{-1} in the control treatment (Table 43). The average daily transpiration rates were 1.9 and 1.6 mm d^{-1} for the control and netted treatments, respectively. Total transpiration from 5 October 2019 to 11 June 2020 was about 466 mm in the open compared to 403 mm under the draped net. This amounts to water use rates of about 4660 and 4030 m^3 ha^{-1}, respectively, and a transpiration-related water saving of 630 m^3 ha^{-1} (-15%). Total seasonal evapotranspiration differed by around 18% between the treatments (Table 43).

5.8.1.2 Yield, pack out and gross income

A summary of the season's results for yield and fruit quality is presented in Table 44. The yield was increased by 6.2% under the net compared to the open, but mean fruit mass was clearly lower under the net treatment. However, the reductions in sunburn and hail damage under the net led to a significant increase in the percentage of fruit delivered to the pack house (as opposed to being culled in the orchard).

The Class 1 and Class 3 packouts were slightly lower under the draped net compared to the open, but the Class 2 packout was higher (Table 45). The average price per ton (taking into account the pack out) was very similar between the treatments, but the higher yield under the net led to a 6% higher gross income per hectare relative to the open treatment.

Table 44 Pack house results for yield, mean fruit mass and other key fruit quality criteria for 'Golden Delicious Reinders' apples grown under back draped net compared to the open during the 2019-2020 season. Data was provided by the pack house.

Variable	Open	Draped Net
Yield (t/ha)	142.7	151.5
Fruit delivered to pack house (%)	90	99
Mean fruit mass (g)	144	130
Sunburn (%)	4.2	1.9
Hail damage (%)	6.2	2.0

Table 45. Differences in packout (grading of fruit into three classes) between open and netted treatments, the mean price achieved for each treatment in R t^{-1}, and the gross income per hectare in R ha^{-1}.

Parameter	Open	Draped Net
Yield and packout		
Yield (t ha^{-1})	142.7	151.5
Class 1	21%	20%
Class 2	74%	77%
Class 3	5%	3%
Price and gross income		
Farm gate price (R t^{-1})	R2989	R2983
R ha^{-1}	R426 478	R451 993

5.8.1.3 Water productivity

The WPp of 'Golden Delicious Reinders' was increased by 9.7% in the 2019-2020 season through the installation of black draped netting between end-November and end-February, compared to the adjacent open orchard (Table 46). This was achieved through a combination of a 6% increase in yield and a 3.3% decrease in seasonal transpiration. The water footprint (WUT) decreased by 8.9%.

From a financial perspective, the WPe increased by 9.6% in the draped net treatment, a very similar result to the WPp (Table 46). The reasons were a combination of a 6% increase in orchard gross income in the net treatment (attributable to the 6% higher yield) and a 3.3% reduction in seasonal transpiration. A set of theoretical prices per class were used, and the results should be regarded as estimates.

The WPp for the whole orchard, based on both transpiration of the fruit trees, evaporation of the soil, and transpiration of the cover crop and weeds (evapotranspiration), is also shown in Table 46. The WPp was 30.5% higher in the net treatment compared to the open, due to the 6.2% increase in yield and the 18.6% decrease in seasonal evapotranspiration. Conversely, the WUT was reduced by 23.4% in the net treatment. The large reduction in ET was the primary reason for a large increase in WPe, since the orchard gross income was only 6% higher in the net treatment compared to the open.

Table 46. Physical Water Productivity (WPp), Water Use per Ton, and Economic Water Productivity (WPe) for the open and draped net treatments at Paardekloof ('Golden Delicious Reinders') in the 2019-2020 season, based on measured transpiration (using sap flow measurements) and modelled evapotranspiration (using soil water balance measurements). Calculations were based on the yield of the whole orchard. Transpiration data was in all cases based on 4 instrumented trees per treatment, and evapotranspiration calculations were based on 2 sampling sites per treatment. The percentage change for netting compared to open is also indicated.

Year	**Physical Water Productivity (WPp) (kg m^{-3})**			**Water Use per Ton (m^3 t^{-1})**			**Economic Water Productivity (WPe) (R m^{-3})**		
Transpiration-based	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**
2020	23.1	25.4	+9.7	43.2	39.4	-8.9	69.2	75.8	+9.6
Evapotranspiration-based	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**
2020	14.5	19.0	+30.5	68.8	52.7	-23.4	43.4	56.6	+30.2

5.8.2 Water productivity – Southfield (EGVV)

5.8.2.1. Seasonal transpiration and evapotranspiration

The maximum average transpiration of the trees without net (control) was around 31.5 L tree^{-1} day^{-1} compared to 30.2 L tree^{-1} day^{-1} under the net (Table 47). The average daily transpiration per tree for the whole period was 20.6 and 17.9 L tree^{-1} day^{-1} for the control and shade net treatments, respectively. Thus, the average transpiration rates of the trees under the net were around 13% lower than those for trees in the open. An average tree under the net transpired about 4 888 litres over the season compared to 5 996 litres in the open. Thus, on average, each tree in the open transpired about 1 110 litres more than under the net. Tree density in the orchard was about 1 250 trees per hectare. Thus, potential water savings as a result of transpiration reductions in all trees in one hectare can be estimated at around 1.4 ML ha^{-1} over the season.

Table 47. Daily and total seasonal transpiration and evapotranspiration in the control and draped nets treatments at Southfield ('Golden Delicious') in 2020-2021.

Parameter	**Mean T (L day^{-1})**		**Mean T (mm day^{-1})**	
	Open	**Draped Net**	**Open**	**Draped Net**
Daily maximum	31.5	30.2	3.9	3.8
Daily average	20.6	17.9	2.6	2.2
Total seasonal	5 996 (L tree^{-1})	4 888 (L tree^{-1})	750 (mm)	611 (mm)
Parameter			**Total ET (mm)**	
			Open	**Netted**
Total seasonal			712.1	826.7

Converting the tree sap flow into equivalent depth units, transpiration under net peaked at 3.8 mm d^{-1} compared to 3.9 mm d^{-1} in the control treatment (Table 47). The average daily transpiration rates were 2.6 and 2.2 mm d^{-1} for the control and netted treatments, respectively. Total transpiration from 01 October 2020 to 30 June 2021 was about 750 mm in the open compared to 611 mm under draped netting. This amounts to water use rates of about 7 495 and 6 110 m^3 ha^{-1}, respectively, and a transpiration-related water saving of 1385 m^3 ha^{-1} (-18.5%). This value for the open orchard compares favourably with the seasonal transpiration values for mature 'Golden Delicious' trees measured by Dzikiti et al. (2018a) in the same orchard.

For the purposes of WP calculations, we show the total seasonal ET in Table 47. The mean values between the two treatments differed by about 16%, being higher under the draped net.

5.8.2.2 Yield, pack out and gross income

Table 48 summarises the key findings that influenced the value of the crop. The yield was higher than expected at the start of the season, above 100 t/ha in both treatments. Although the mean yield was higher for the trees under draped net, the treatment difference was not significant. The slightly higher yield under the net was linked to a smaller mean fruit mass compared to the control. The apples were generally small, as was previously found for this orchard (Dzikiti et al., 2018a). However, there were no other significant defects except sunburn, which was strongly reduced under the draped net. Based on the significantly greater sunburn in the control, notwithstanding the slightly larger mean fruit size, we used lower estimates of the proportion of fruit in Classes 1 and 2, and a higher estimate of the proportion in Class 3 (Table 49. The analysis of farm gate price (mean for all fruit) and gross income is also shown in Table 49. The results, in terms of treatment differences, are well aligned with results obtained in the previous two seasons of this study. Gross value was estimated to be increased by 33% under the draped net.

Table 48 Results for yield, mean fruit mass and other economically significant fruit quality criteria for 'Golden Delicious' apples grown under black draped net compared to the open during the 2020-2021 season. Data was for the ten trees monitored in each treatment.

Variable	Open	Draped Net
Yield (t/ha)	102.1	116.5
Mean fruit mass (g)	90.5	83.3
Sunburn Class 0 (no sunburn) (%)	49.5	93.5
Sunburn Classes 1-4 (%)	29.0	5.0
Sunburn Classes 5-8 (%)	21.5	1.5

Table 49. Estimated differences in packout (grading of fruit into three classes) between open and netted treatments, the mean price achieved for each treatment in R t^{-1}, and the gross income per hectare in R ha^{-1}. Estimated mean prices were: Class 1 – R4500/ton; Class 2 – R2500/ton; Class 3 – R1500/ton. Final figures for packout and prices are awaited from the pack house.

	Open	Draped Net
Packout		
Class 1	10%	20%
Class 2	65%	75%
Class 3	25%	5%
Price and gross income		
Farm gate price (R t^{-1})	R 2450	R 2850
R ha^{-1}	R 200 165	R 265 620

5.8.2.3 Water productivity

The use of black draped netting over the 'Golden Delicious' orchard at Southfield, Villiersdorp, in 2020-2021 increased the WPp by approximately 34% (Table 50). This was a larger increase than that found in the first two seasons in the Koue Bokkeveld. In the first trial with black draped netting over a 'Golden Delicious Reinders' orchard in 2019-2020 the WPp was increased by around 10%.

The large increase reported here was achieved through a combination of a 14% higher yield and a 14.7% lower seasonal transpiration. The water footprint (WUT) decreased by 25.2%.

From a financial perspective, the WPe was estimated to increase by 55% in the draped net treatment (Table 50). The reasons were a combination of an estimated 33% increase in orchard gross income in the net treatment (attributable to the large reduction in sunburn and a higher yield) and a 14.7% measured reduction in seasonal transpiration. A set of theoretical prices per class were used, and the results should be regarded as a broad estimate.

The WPp for the whole orchard, based on both transpiration of the fruit trees, evaporation of the soil, and transpiration of the cover crop and weeds (evapotranspiration), is also shown in Table 50. The WPp was around 2% lower in the draped net treatment compared to the open, due to the higher seasonal evapotranspiration in this treatment compared to the control. Conversely, the WUT was increased by around 2% in the net treatment. However, these numbers are very likely within the margin of error for the whole study. There was an estimated 14% increase in WPe, driven by the differential between increased (33%) gross income and increased ET (16%).

Table 50. Physical Water Productivity, Water Use per Ton, and Economic Water Productivity for the open and fixed net treatments at Southfield in the 2020-2021 season, based on measured transpiration (using sap flow measurements) and modelled evapotranspiration (using soil water balance measurements). Calculations were based on the yield of the ten monitored trees per treatment. Transpiration data was in all cases based on 4 instrumented trees per treatment, and evapotranspiration calculations were based on 2 sampling sites per treatment. The percentage change for netting compared to open is also indicated.

Year	Physical Water Productivity (kg m^{-3})			Water Use per Ton (m^3 t^{-1})			Economic Water Productivity (R m^{-3})		
Transpiration-based	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**
2021	12.6	16.8	33.7	79.5	59.5	-25.2	24.6	38.3	55.5
Evapotranspiration-based	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**	**Open**	**Netted**	**% change**
2021	14.3	14.1	-1.7	69.7	71.0	1.8	28.1	32.1	14.3

5.9 BUDGETING LIFETIME COSTS AND INCOME OF ORCHARDS IN THE OPEN AND UNDER DRAPED NETTING

Table 51 Cumulative profit per scenario for open and drape netted 'Golden Delicious Reinders' apple orchards. The blue scenarios are based on the actual orchard used in the study, starting in 2009. The orange scenarios are a theoretical orchard planted in 2020.

	Open	**Net**	**Difference**
Scenario 1	R 3 260 113	R 4 011 057	R 750 944
Scenario 2	R 2 098 437	R 2 711 392	R 612 955
Scenario 3	R 3 103 968	R 3 803 146	R 699 178
Scenario 4	R 3 251 867	R 4 373 750	R 1 121 883
Scenario 5	R 3 251 867	R 4 169 960	R 918 093
Scenario 6	R 3 125 188	R 4 334 568	R 1 209 380
Scenario 7	R 2 973 925	R 4 287 783	R 1 313 858

The 'Golden Delicious Reinders' orchard at Paardekloof was established in 2009. The first three scenarios are based on the actual yield obtained in this orchard from planting until 2020 (Year 11), the harvest after the draped netting was installed for the first time (2019, Year 10). Thereafter, the model yield inputs are estimated. The orchard showed a slow start to achieving expected yields, but by Year 8 the yield had exceeded 100 t ha^{-1} and a very high yield of 141 t ha^{-1} was recorded in 2020. The impact of these yields can be seen in Figure 129. The installation of the draped net in Year 10 reflects as a dip in profit (this is hypothetical since the netting was donated for the purposes of this research). Thereafter, assuming that the net is re-used annually, without replacement, and an annual yield of 120 t ha^{-1} is achieved for both treatments, annual profits are higher under the net compared to the open. This is attributable to the OR of 98% under netting (fruit sent to the pack house) compared to 92% in the open (based on the results recorded at harvest in 2020), as well as a higher percentage Class 1 and Class 2 fruit, and a lower percentage Class 3 fruit under the net compared to the open. The modelled increase in cumulative profit over 25 years for the netted orchard compared to the open orchard is R750 944 (Table 51).

Figure 130 (scenario 2) clearly shows the dominant influence of orchard lifetime yield on cumulative profit. This scenario differs from the one above (scenario 1) only in yield achieved from 2021 onwards (100 t ha^{-1} and 120 t ha^{-1}, respectively). The cumulative profit is significantly reduced (below R2.8 million) in both treatments, with the netted orchard achieving R612 955 greater cumulative profit relative to the open orchard (Table 51).

For scenario 3 (Figure 131), more conservative pack out results were used compared to scenario 1, but with the same yield of 120 t ha^{-1}. Annual and cumulative profit were slightly lower in scenario 3 and the final difference between netted and open orchards was R699 178 (Table 51).

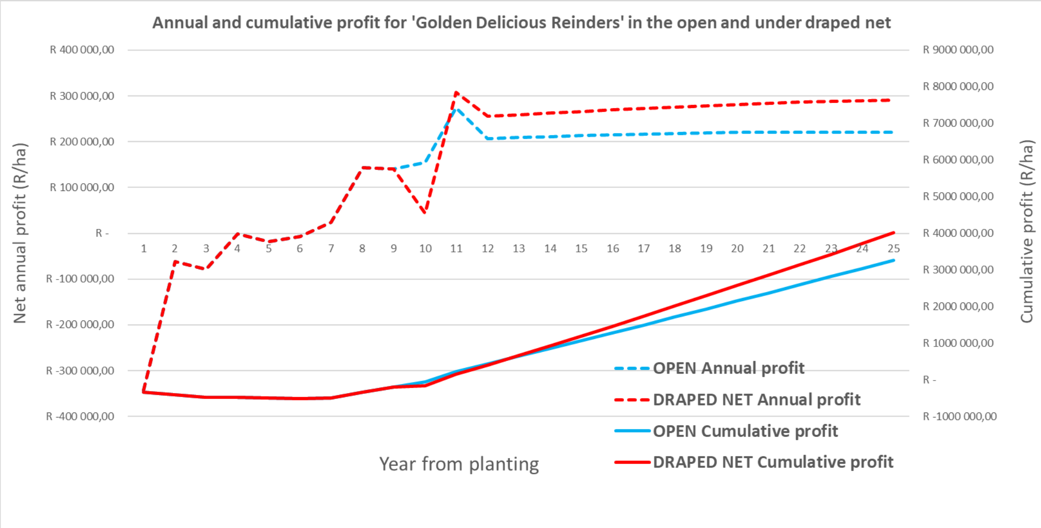


Figure 129 Net annual and cumulative profit for a 'Golden Delicious Reinders' apple orchard under Scenario 1.

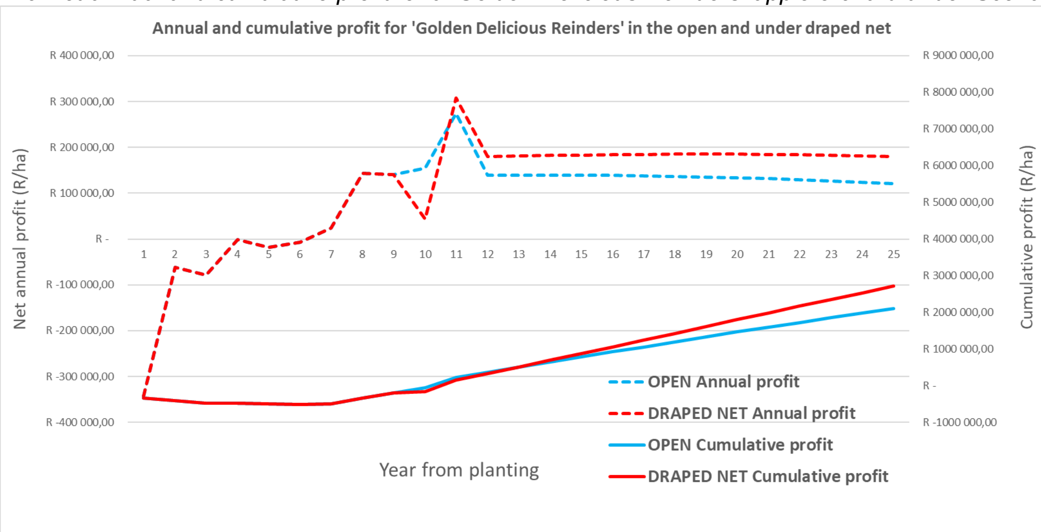


Figure 130 Net annual and cumulative profit for a 'Golden Delicious Reinders' apple orchard under Scenario 2.

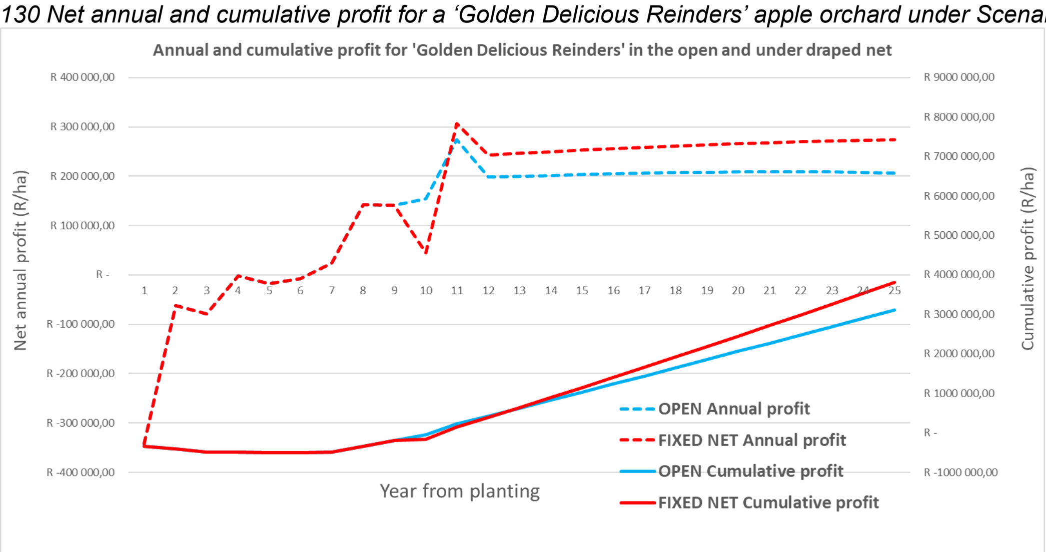


Figure 131 Net annual and cumulative profit for a 'Golden Delicious Reinders' apple orchard under Scenario 3.

The following figures (Figure 132 to Figure 135) represent the modelling results for scenarios 4-7. These scenarios represent theoretical orchards established in 2020, with draped netting first installed in Year 3 and every year thereafter. In scenarios 4, 6 and 7 the draped net is replaced once, in Year 2036. The industry generally expects draped netting to last for about 15 years. In scenario 5 the net is replaced twice in Years 2030 and 2038, simulating a situation where the net suffers severe damage from a storm. The cost of purchasing draped netting can be seen in the figures as noticeable dips in the dotted red lines, and slight dips in the solid red lines.

The highest absolute cumulative profit is achieved with draped net replaced once, and no very severe hail or sunburn events during the orchard lifetime (scenario 4, Figure 132). The cumulative profit difference between the netted and control treatments is estimated at R1 121 883 (Table 51). The cost of a second net replacement is seen in Figure 133 (scenario 5), bringing the benefit down to R918 093. Where one severe event (hail or sunburn) is added to the model in Year 10 (Figure 134), differentially affecting the outcome in open and netted treatments (comparison between scenario 6 against scenario 4), the difference in cumulative profit grows to R1 209 380. The biggest benefit of netting is seen in scenario 7 (R1 313 959) where two such events are experienced over the orchard lifetime (Figure 135). The benefit of installing draped nets thus increases with every hail/sunburn event experienced and is thus maximised in areas where these risks are high.

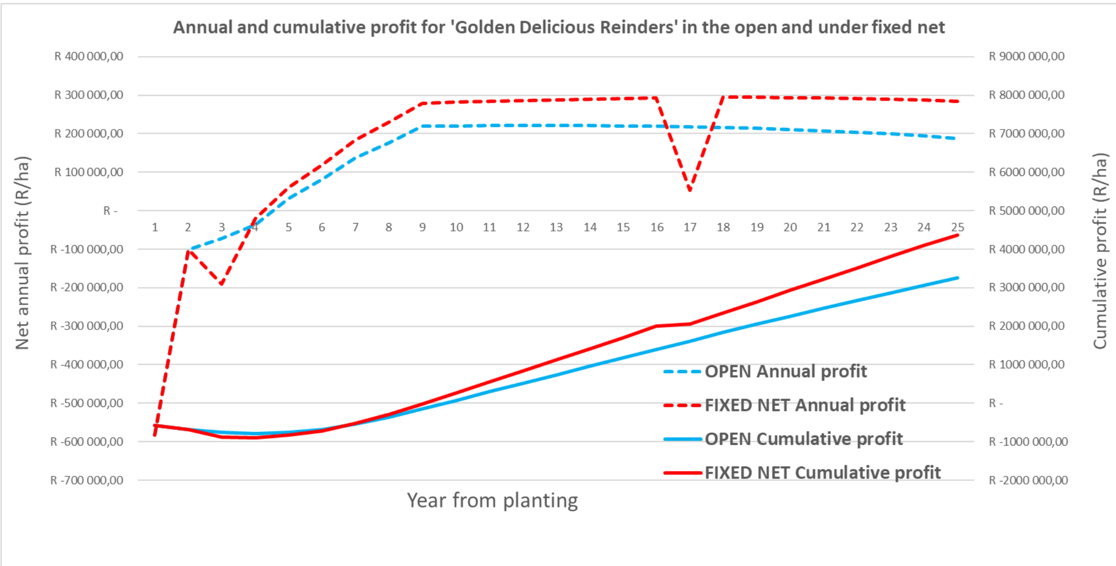


Figure 132 Net annual and cumulative profit for a 'Golden Delicious Reinders' apple orchard under Scenario 4.

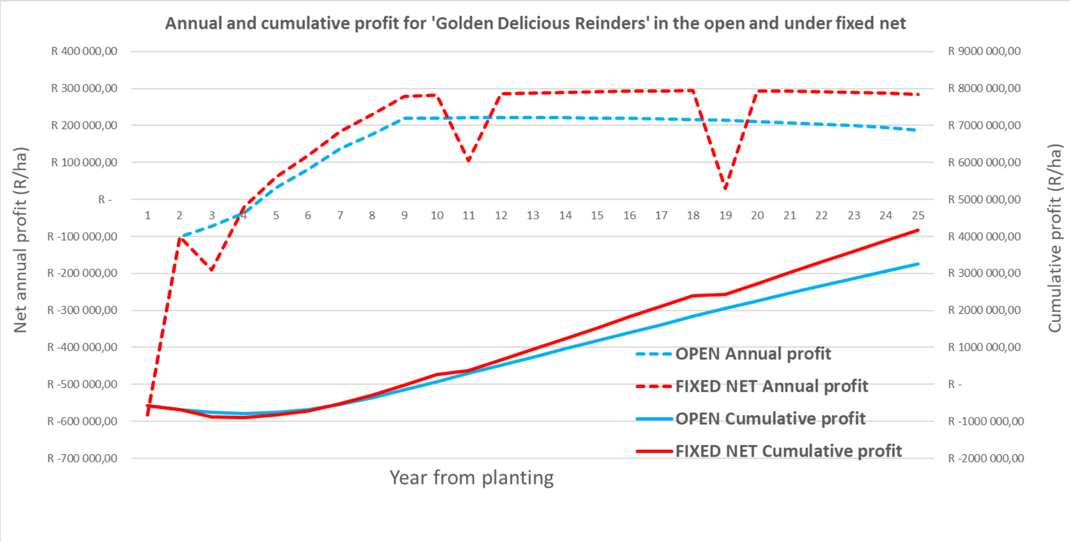


Figure 133 Net annual and cumulative profit for a 'Golden Delicious Reinders' apple orchard under Scenario 5.

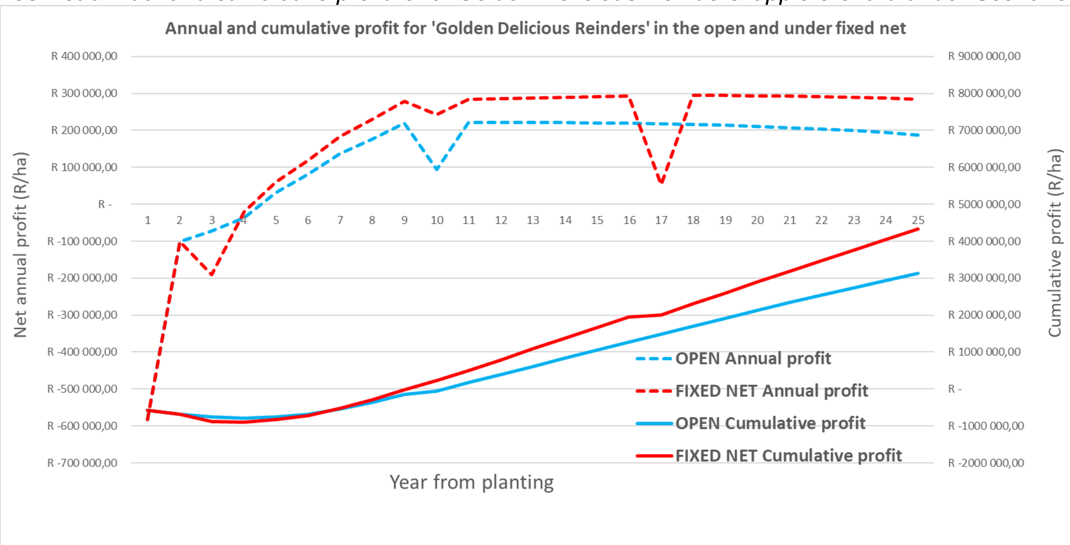


Figure 134 Net annual and cumulative profit for a 'Golden Delicious Reinders' apple orchard under Scenario 6.

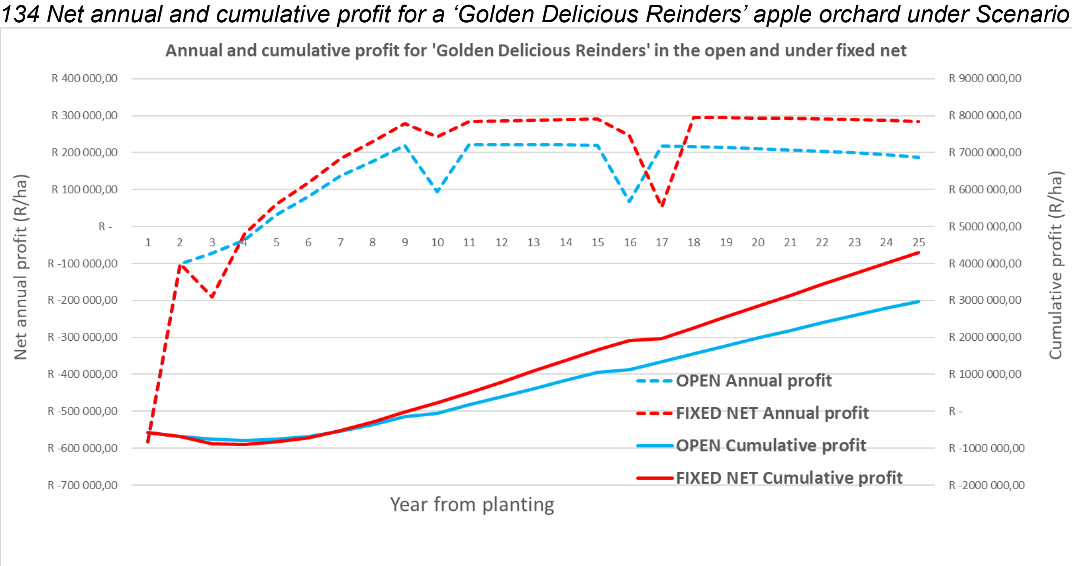


Figure 135 Net annual and cumulative profit for a 'Golden Delicious Reinders' apple orchard under Scenario 7.

CHAPTER 6: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 General discussion

Both types of netting altered the orchard microclimate, but to varying extents. Averaged over two seasons, the fixed nets reduced daily total solar radiation by ~ 12%, wind speed by more than 36%, and reference evapotranspiration by ~ 12%. Seasonal T was ~ 11% lower under nets, while ET was only ~ 4% lower (Table 52). The differences in air temperature and relative humidity between the two treatments were very small, likely because of the small size of the fixed netted area. While the lower transpiration rates under the nets were expected, and they mirrored the changes in the atmospheric evaporative demand, the small difference in ET between netted and open orchards was rather surprising. Given that microlysimeter measurements of soil evaporation showed significantly lower soil evaporation under the fixed nets, the small ET difference can only be explained by a much more active vegetation cover on the orchard floor under the nets than in the open. This result suggests that while the fixed nets reduced tree level water use rates, careful management of the orchard floor is essential to maximize the water saving benefits of fixed nets. There is a higher likelihood of more vigorous weed and cover crop growth under the fixed nets than in the open, possibly due to more favourable growth conditions, i.e. milder microclimate and relatively wetter soils.

This observation is further supported by the performance of the modified Shuttleworth and Wallace model (Dzikiti et al., 2018) in which the transpiration component under both treatments was accurately predicted, but the model significantly under-estimated the orchard floor evaporation, and hence ET under the nets. Another confounding factor in this study could be the substantially higher irrigation levels that were applied under nets than the control treatment, creating a wetter micro-environment. However, the possibility of much more growth of weeds and cover crops under the fixed nets should be investigated in future studies as these tend to diminish the water saving benefits of the fixed nets.

Based on transpiration measurements, the physical water productivity (kg of fruit per m^3 of water transpired) was 14-15% higher under the nets, while this benefit was much smaller (~ 1%) when calculated on an ET basis. The economic water productivity (Rand per m^3 of water transpired) ranged between 20 and 45%, while no meaningful treatment difference was found when the calculations were based on ET. Observations on yield and fruit quality under fixed nets confirmed findings from earlier studies.

The draped nets reduced the solar radiation within the tree canopies by an even larger proportion (30-35%), presumably because of the higher shade factor (~ 24%). The air temperature was on average 1-2°C cooler while the relative humidity remained 5-10% higher under the nets. The higher relative humidity can be explained by the poor air circulation under the nets and transpiration of water vapour from the trees which gets trapped under the nets. The effect of this was a decrease in the vapour pressure deficit of air under the nets by between 0.1 and 0.2 kPa which reduced the atmospheric evaporative demand. Transpiration declined by ~ 9% under the draped nets (Table 52). This figure is an average over two seasons, but also from two different sites.

The difference in water use based on ET data were mixed between the two seasons likely because of methodological limitations. It was difficult to accurately predict the deep drainage component in the soil water balance calculation which may explain some of the differences, especially given the very high irrigation levels in some orchards. With much more precise needs-driven irrigation practices (i.e. avoidance of over-irrigation and deep drainage) of drape netted orchards it is likely that changes in ET would support a greater water use savings. Yield was higher under the draped nets, varying between 6% (farm data, 2020, linked to smaller fruit size) and 14% (trial data, 2021, not significantly different) between the years and sites.

Table 52 Summary of the seasonal water use of apple orchards in the three trials over three seasons, 2018-2019, 2019-2020 and 2020-2021. T represents orchard level transpiration, and ET represents the orchard evapotranspiration. Transpiration data was derived from sap flow measurements while ET was modelled using the Shuttleworth and Wallace model. Irrigation rates, yield, physical water productivity and economic water productivity are also presented. Water productivity was calculated on the basis of T and ET. Percentage differences between the control and net treatments are given.

	Site 1: Fixed white netting 'Rosy Glow' 2018-2019	**Site 1: Fixed white netting 'Rosy Glow' 2019-2020**	**Site 2: Black draped netting 'Golden Delicious Reinders' 2019-2020**	**Site 3: Black draped netting 'Golden Delicious' 2020-2021**
T (m^3 ha^{-1}) (Oct-May)	Open: 5 810 Net: 5 330 Difference: -8%	Open: 6429 Net: 5462 Difference: -15%	Open: 6168 Net: 5966 Difference: -3%	Open: 8121 Net: 6930 Difference: -15%
ET (m^3 ha^{-1}) (July-June)	n.a.	Open: 9919 Net: 9845 Difference: -1%	Open: 9819 Net: 7990 Difference: -19%	Open: 7121 Net: 8267 Difference: +16%
Irrigation (m^3 ha^{-1}) (Oct-May)		Open: 9 359 Net: 10 443 Difference: +12%	Open: 7511 Net: 6797 Difference: +9.5%	Open: 6006 Net: 6142 Difference: -2.3%
Yield (t ha^{-1})	Open: 132.3 Net: 138.7 Difference: +4.8%	Open: 113.5 Net: 110.6 Difference: -2.6%	Open: 142.7 Net: 151.5 Difference: +6.2%	Open: 102.1 Net: 116.5 Difference: +14.1%
Physical water productivity (kg m^{-3}) T-based	Open: 22.8 Net: 26.0 Difference: +14.3%	Open: 17.7 Net: 20.3 Difference: +14.7%	Open: 23.1 Net: 25.4 Difference: +9.7%	Open: 12.6 Net: 16.8 Difference: +33.7%
Economic water productivity (R m^{-3}) T-based	Open: 80.1 Net: 114.6 Difference: +43.2%	Open: 86.6 Net: 104.6 Difference: +20.8%	Open: 69.2 Net: 75.8 Difference: +9.6%	Open: 24.6 Net: 38.3 Difference: +55.5%
Physical water productivity (kg m^{-3}) ET-based	n.a.	Open: 11.4 Net: 11.2 Difference: -1.8%	Open: 14.5 Net: 19.0 Difference: +30.5%	Open: 14.3 Net: 14.1 Difference: -1.7%
Economic water productivity (R m^{-3}) ET-based	n.a.	Open: 56.1 Net: 58.0 Difference: +3.4%	Open: 43.4 Net: 56.6 Difference: +30.2%	Open: 28.1 Net: 32.1 Difference: +14.3%

6.2 Conclusions

Protective netting installed over apple orchards in the Western Cape of South Africa has very clear benefits for production and marketable yield, and thus farm income, even when considering the costs of installation and maintenance. This study has confirmed that a saving in water use per hectare and per ton of fruit in high-yielding irrigated apple orchards is possible, adding to the other benefits of this technology. While the results were influenced by net type (fixed white, black draped), cultivars, tree age/size, production region, and season, a reduction in orchard level transpiration of between 3% and 15% was found under netting compared to the open control across three orchards. Orchard evapotranspiration differed more widely, between a reduction of 19% and an increase of 16%. Thus, absolute water savings varied. Physical water productivity (kg m^{-3}) based on transpiration was consistently increased (10-34%); but the values based on evapotranspiration ranged from no effect to a 30% increase. Economic water productivity (R m^{-3}) showed clear benefits of netting, with increases of 3-30% based on evapotranspiration.

Challenges with complex measurement techniques and other factors, such as optimised irrigation scheduling for the two treatments, lead us to conclude that these results should be regarded as an initial indication of potential water use savings under nets. The moderate savings achieved are likely partially explained by the microclimatic dynamics under the nets used. A relatively small area of fixed netting with open sides, and draped netting that only covers the canopy, result in no other changes in microclimate except a reduction in solar radiation and wind speed. Thus, evapotranspiration is not clearly reduced, especially where applied irrigation may be more than required. Very precise irrigation under nets is likely to yield greater water savings benefits. There was also some evidence to suggest that more vigorous growth of the cover crop under the fixed net contributed to a higher orchard evapotranspiration, and that a greater water savings may be achieved with adjusted cover crop management.

6.3 Recommendations

Based on the results of this study, the following recommendations can be made:

1) Orchard size seems to influence the microclimate and hence the water savings under fixed nets. This idea needs to be investigated further to make recommendations on the minimum fixed nets size required to achieve significant water savings.

2) Do fixed nets indeed promote more active ground cover? If so, what are the implications on water savings from this type of net?

3) This study only investigated the effects of fixed and draped nets on two apple cultivars namely 'Golden Delicious'/'Golden Delicious Reinders' and 'Rosy Glow'. How effective is this technology on other cultivars?

4) What are the effects of closing the sides of a fixed net in terms of microclimate, water savings and fruit quality?

APPENDIX A. REFERENCES

Alarcón, J.J., Ortuño, M.F., Nicolás, E., Navarro, A. and Torrecillas, A., 2006. Improving water-use efficiency of young lemon trees by shading with aluminised-plastic nets. Agricultural Water Management 82: 387-398.

Allen, R.G., Pereira L.S., Raes D., Smith M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome, Italy. 300 pp.

Baker, J.M. and van Bavel, C.H.M., 1987. Measurement of mass flow of water in stems of herbaceous plants. Plant, Cell and Environment 10: 777-782.

Baraldi, R., Rossi, F., Facini, O., Fasolo, F., Rotondi, A., Magli, M. and Nerozzi, F., 1994. Light environment, growth and morphogenesis in a peach tree canopy. Physiologia Plantarum 91: 339-345.

Basile, B., Giaccone, M., Cirillo, C., Ritieni, A., Graziani, G., Shahak, Y. and Forlani, M., 2012. Photo-selective hail nets affect fruit size and quality in Hayward kiwifruit. Scientia Horticulturae 141: 91-97.

Basile, B., Giaccone, M., Shahak, Y., Forlani, M. and Cirillo, C., 2014. Regulation of the vegetative growth of kiwifruit vines by photo-selective anti-hail netting. Scientia Horticulturae 172: 300-307.

Bastías, R.M. and Corelli-Grappadelli, L., 2012. Light quality management in fruit orchards: physiological and technological aspects. Chilean Journal of Agricultural Research 72: 574-582.

Bastías, R.M., 2011. Morphological and physiological responses of apple trees under photoselective colored nets. PhD thesis. Università di Bologna, Italy.

Bastías, R.M., Manfrini, L. and Grappadelli, L.C., 2012. Exploring the potential use of photoselective nets for fruit growth regulation in apple. Chilean Journal of Agricultural Research 72: 224-231.

Bastidas-Obando, E., Bastiaanssen, W.G.M., Jarmain, C., 2017. Estimation of transpiration fluxes from rain fed and irrigated sugarcane in South Africa using a canopy resistance and crop coefficient model. Agricultural Water Management 181: 94-107.

Bauerle, W., Post, C.J., McLeod, M.F., Dudley, J.B., Toler, J.E., 2002. Measurement and modelling of the transpiration of a temperate red maple container nursery. Agricultural and Forest Meteorology 114: 45-57.

Bepete, M. and Lakso, A.N., 1998. Differential effects shade on early-season fruit and shoot growth rates in “Empire” apple. HortScience 33: 823-825.

Bergh, O., 1985a. Morphogenesis of *Malus domestica* cv. Starking flower buds. South African Journal of Plant and Soil, 2(4):187-190.

Blake, G.R. and Hartge, K.H. 1986. Bulk Density: Core Method. Methods of soil analysis, part 1. p. 364-367. In Physical and mineralogical methods – Agronomy monograph no. 9 (2nd edition).

Blanke, M., 2008. Alternatives to reflective mulch cloth (ExtendayTM) for apple under hail net? Scientia Horticulturae 116: 223-226.

Blanke, M., 2009. The structure of coloured hail nets affects light transmission, light spectrum, phytochrome and apple fruit colouration. Acta Horticulturae 817: 177-184.

Boini, A., Muzzi, E., Tixier, A., Zwieniecki, M., Manfrini, L. and Grappadelli, L.C., 2021. Photoselective nets alter apple canopy air temperature and carbon translocation during dormancy and budbreak. HortScience, 56(10):1166-1174.

Bosco, L.C., Bergamaschi, H., Cardoso, L.S., de Paula, V.A., Marodin, G.A.B. and Brauner, P.C., 2018. Microclimate alterations caused by agricultural hail net coverage and effects on apple tree yield in subtropical climate of Southern Brazil. Bragantia, Campinas 77: 181-192.

Brink, D., Kotze, W. and Steyn, W., 2015. Do shade nets ease the burn or do they burn a hole through your pocket? Findings of a study in the EGVV on the use of shade netting to reduce sunburn in apple. South African Fruit Journal, Dec/Jan 2015, pp. 79-82.

Brown, R. 2018. Effect of permanent shade netting on ‘Nadorcott’ mandarin tree phenology and productivity. MSc (Horticultural Science) thesis, Stellenbosch University, Stellenbosch.

Brutnell T., 2006. Phytochrome and control of plant development. In: L. Taiz and E. Zeiger (Eds). Plant Physiology, 4th edn. Sinauer Associated, Inc., Sunderland, pp 417-440.

Burgess, S.S.O., Adams, M.A., Turner, N.C., Beverly, C.R., Ong, C.K., Khan, A.A.H. and Bleby, T.M., 2001. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. Tree Physiology 21: 589-598.

Castellano, S., Candura, A. and Mugnozza, G.S., 2008. Relationship between solidity ratio, colour and shading effect of agricultural nets. Acta Horticulturae 801: 253-258.

Castellano, S., Russo, G. and Mugnozza, G.S., 2006. The influence of construction parameters on radiometric performances of agricultural nets. Acta Horticulturae 718: 283-290.

Chenafi, A., Monney, P., Arrigoni, E., Boudoukha, A., Carlen, C., 2016. Influence of irrigation strategies on productivity, fruit quality and soil-plant water status of subsurface drip-irrigated apple trees. Fruits 71 (2), 69-78.

Cheng, L. and Luo, X., 1997. Diurnal and seasonal stomatal regulation of water use efficiency in leaves on field-grown apple trees. Acta Horticulturae, 451: 375-382.

Cohen, S., Moreshet, S., Guillou, L.L., Simon, J.C. and Cohen, M., 1997. Response of citrus trees to modified radiation regime in semi-arid conditions. Journal of Experimental Botany 48: 35-44.

Cohen, S., Naor, A., 2002. The effect of three rootstocks on water use, canopy conductance and hydraulic parameters of apple trees and predicting canopy from hydraulic conductance. Plant, Cell and Environment 25, 17-28.

Comstock, J.P. and Ehleringer, J.R., 1992. Correlating genetic variation in carbon isotopic composition with complex climatic gradients. Proceedings of the National Academy of Sciences of the USA 89: 7747-7751.

Conceição, M.A.F., Marin, F.R., 2009. Microclimate conditions inside an irrigated vineyard covered with a plastic screen. Revista Brasileira de Fruticultura 31, 423-431.

Cook, N.C. and Jacobs, G. 2000. Progression of apple (Malus x domestica Borkh.) bud dormancy in two mild winter climates. Journal of Horticultural Science and Biotechnology 75: 233-236.

Cook, N.C., 2007, October. Apple production under conditions of sub-optimal winter chilling in South Africa. Acta Horticulturae, 872:199-204.

Corelli-Grappadelli, L. and Lakso. A.N., 2007. Is maximizing orchard light interception always the best choice? Acta Horticulturae 732: 507-518.

Corelli-Grappadelli, L. C., 2003. Light Relations. In: D.C. Ferree and I.J. Warrington (eds). Apples: Botany, Production and Uses. CAB International. pp. 195-216.

Corelli-Grappadelli, L., Lakso, A.N. and Flore, J.A., 1994. Early season pattern of carbohydrate partitioning in exposed and shaded apple branches. Journal of the American Society of Horticultural Science, 119: 596-603.

Crété, X., Regnard, J.L., Ferre, G. and Tronel, C., 2001. Effects secondaires et conséquences sur la conduite du verger. L'arboriculture fruitière 553: 51-55.

Daamen, C.C., Simmonds, L.P., Wallace, J.S., Laryea, K.B. and Sivakumar, M.V.K., 1993. Use of microlysimeters to measure evaporation from sandy soils. Agricultural and Forest Meteorology 65: 159-173.

De Freitas, S.T., do Amarante, C.V.T., Dandekar, A.M. and Mitcham, E.J., 2013. Shading affects flesh calcium uptake and concentration, bitter pit incidence and other fruit traits in 'Greensleeves' apple. Scientia Horticulturae 161: 266-272.

De Paula, V.A., Bergamaschi, H., del Ponte, E.M., Cardoso, L.S. and Bosco, L.C., 2012. Leaf wetness duration in apple orchards in open sky and under hail net cover, in Vacaria, Brazil. Revista Brasileira de Fruticultura 34: 451-459.

De Wit, M., Galvão, V.C. and Fankhauser, C., 2016. Light-mediated hormonal regulation of plant growth and development. Annual Review of Plant Biology 67: 513-537.

Dennis, F.G., 2003. Flowering, pollination and fruit set and development. In: D.C. Ferree and I.J. Warrington (eds). Apples: Botany, Production and Uses. CAB International. pp. 153-166.

Do Amarante, C.V.T., Steffens, C.A. and Argenta, L.C., 2011. Yield and fruit quality of 'Gala' and 'Fuji' apple trees protected by white anti-hail net. Scientia Horticulturae 129: 79-85.

Dussi, M.C., Giardina, G., Sosa, D., Reeb, P., 2005. Shade nets effect on canopy light distribution and quality of fruit and spur leaf on apple cv. Fuji. Spanish Journal of Agricultural Research 3: 253-260.

Dzikiti, S., Gush, M.B., Taylor, N.J., Volschenk, T., Midgley, S.J.E., Lötze, E., Schmeisser, M., Doko, Q. 2017. Measurement and modelling of water use by high yielding apple orchards and orchards of different age groups in the winter rainfall areas of South Africa. Acta Horticulturae 1150: 31-37.

Dzikiti, S., Verreynne, J.S., Strever, A., Stuckens, J., Verstraeten, W.W., Swennen, R., Theron, K.I. and Coppin, P., 2011. Seasonal variation in canopy reflectance and its application to determine the water status and water use by citrus orchards in the Western Cape, South Africa. Agricultural and Forest Meteorology 151: 1035-1044.

Dzikiti, S., Volschenk, T., Midgley, S., Gush, M., Taylor, N., Lötze, E., Zirebwa, S., Ntshidi, Z., Mobe, N., Schmeisser, M. and Doko, Q. (2018a) Quantifying water use and water productivity of high performing apple orchards of different canopy sizes in winter rainfall areas of South Africa. WRC Report TT 751-2018. Final Project Report to the Water Research Commission and Hortgro Science.

Dzikiti, S., Volschenk, T., Midgley, S.J.E., Lötze, E., Taylor, N.J., Gush, M.B., Ntshidi, Z., Zirebwa, S.F., Doko, Q., Schmeisser, M., Jarmain, C., Steyn, W.J. and Pienaar, H.H., 2018b. Estimating the water requirements of high yielding and young apple orchards in the winter rainfall areas of South Africa using a dual source evapotranspiration model. Agricultural Water Management 208: 152-162.

Ebert, G. and Casierra, F., 2000. Does netting always reduce the assimilation of apple trees? (Verringert die Einnetzung grundsätzlich die Assimilationsleistung von Apfelbäumen?). Erwerbs-Obstbau 42: 12-14.

Egea, G., Verhoef, A., Vidale, P.L., 2011. Towards an improved and more flexible representation of water stress in coupled photosynthesis-stomatal conductance models. Agricultural and Forest Meteorology 151: 1370-1384.

Farquhar, G.D., Ehleringer, J.R. and Hubick, K.T., 1989. Carbon isotope discrimination and photosynthesis. Annual Review of Plant Physiology and Plant Molecular Biology 40: 503-537.

Fernandez, E., Luedeling, E., Behrend, D., Van de Vliet, S., Kunz, A. and Fadón, E., 2020. Mild water stress makes apple buds more likely to flower and more responsive to artificial forcing—impacts of an unusually warm and dry summer in Germany. Agronomy, 10(2):274.

Giaccone, M., Forlani, M. and Basilea, B., 2012. Tree vigor, fruit yield and quality of nectarine trees grown under red photoselective anti-hail nets in Southern Italy. Acta Horticulturae 962: 387-393.

Gilbert, I.R., Jarvis, P.G. and Smith, H., 2001. Proximity signal and shade avoidance differences between early and late successional trees. Nature 411: 792-794.

Gindaba, J. and Wand, S.J.E., 2005. Comparative effects of evaporative cooling, kaolin particle film, and shade net on sunburn and fruit quality in apples. HortScience 40: 592-596.

Gindaba, J. and Wand, S.J.E., 2007a. Climate-ameliorating measures influence photosynthetic gas exchange of apple leaves. Annals of Applied Biology 150: 75-80.

Gindaba, J. and Wand, S.J.E., 2007b. Do fruit sunburn control measures affect leaf photosynthetic rate and stomatal conductance in 'Royal Gala' apple? Environmental and Experimental Botany 59: 160-165.

Girona, J., Behboudian, M.H., Mata, M., Del Campo, J. and Marsal, J., 2012. Effect of hail nets on the microclimate, irrigation requirements, tree growth, and fruit yield of peach orchards in Catalonia (Spain). The Journal of Horticultural Science and Biotechnology 87: 545-550.

Goodwin, I. and Green, S., 2012. Irrigation requirement in a netted apple orchard. Horticulture Australia, May 2012.

Gouws, A. and Steyn, W.J., 2014. The effect of temperature, region and season on red colour development in apple peel under constant irradiance. Scientia Horticulturae 173: 79-85.

Granier, A., 1985. Une nouvelle methode pour la mesure du flux de seve brute dans le tronc des arbres. Annales des Sciences Forestieres 42: 193-200.

Green, S.R., McNaughton, K.G., Wünsche, J.N. and Clothier, B.E., 2003. Modelling light interception and transpiration of apple tree canopies. Agronomy Journal 96: 1380-1387.

Greybe, E. and Bergh, O., 1998. The effect of winter chilling on cell division and multiplication pre-anthesis and thus on final fruit size of Royal Gala apples in South Africa. Acta Horticulturae, 519:113-120.

Gush, M.B. and Taylor, N.J., 2014. The water use of selected fruit tree orchards (Volume 2): Technical report on measurements and modelling. Water Research Commission Report No.1770/2/14, WRC, Pretoria, RSA.

Hättasch, C., Flachowsky, H., Kapturska, D. and Hanke, M.V., 2008. Isolation of flowering genes and seasonal changes in their transcript levels related to flower induction and initiation in apple (*Malus domestica*). Tree Physiology, 28(10):1459-1466.

Heide, O.M., Rivero, R. and Sønsteby, A., 2020. Temperature control of shoot growth and floral initiation in apple (Malus × domestica Borkh.). CABI Agriculture and Bioscience, 1(1):1-15.

Hengari, S., Theron, K.I., Midgley, S.J.E. and Steyn, W.J., 2014. Response of apple (*Malus domestica* Borkh.) fruit peel photosystems to heat stress coupled with moderate photosynthetic active radiation at different fruit development stages. Scientia Horticulturae 178: 154-162.

Hortgro Science, 2018. Hortgro Technical Symposium – the big thirst. Summary Report. Hortgro Science, Stellenbosch.

Hortgro, 2021. Key deciduous fruit statistics 2020. Hortgro, Paarl.

Hunsche, M., Blanke, M.M. and Noga, G., 2010. Does the microclimate under hail nets influence micromorphological characteristics of apple leaves and cuticles? Journal of Plant Physiology 167: 974-980.

Iglesias, I. and Alegre, S., 2006. The effect of anti-hail nets on fruit protection, radiation, temperature, quality and profitability of 'Mondial Gala' apples. Journal of Applied Horticulture 8: 91-100.

Jackson, J.E., 1980. Light interception and utilization by orchard systems. Horticultural Reviews 2: 208-267.

Jackson, J.E., 2003. The Biology of Apples and Pears. Cambridge University Press, Cambridge, United Kingdom.

Jarvis, P.G. and McNaughton, K.G., 1986. Stomatal control of transpiration: scaling up from leaf to region. Advances in Ecological Research 15: 1-45.

Jarvis, P.G., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences 273: 593-610.

Jarvis, P.G., 1985. Coupling of transpiration to the atmosphere in horticultural crops: the omega factor. Acta Horticulturae 171: 187-205.

Jifon, J.L. and Syvertsen, J.P., 2003. Moderate shade can increase net gas exchange and reduce photoinhibition in citrus leaves. Tree Physiology 23: 119-127.

Jones, H.G., Lakso, A.N. and Syvertsen, J.P., 1985. Physiological control of water status in temperate and subtropical fruit trees. Horticultural Reviews 7: 302-343.

Kalcsits, L., Musacchi, S., Layne, D.R., Schmidt, T., Mupambi, G., Serra, S., Mendoza, M. and Asteggiano, L., 2017. Above and below-ground environmental changes associated with the use of photoselective protective netting to reduce sunburn in apple. Agricultural and Forest Meteorology 238: 9-17.

Koutinas, N., Pepelyankov, G. and Lichev, V., 2010. Flower induction and flower bud development in apple and sweet cherry. Biotechnology & Biotechnological Equipment, 24(1):1549-1558.

Lakatos, L., Gonda, I., Soltész, M., Szabó, Z., Szél, J., Nyéki, J., 2011. Effects of excessive weather on the micro-climate of apple plantations under the hail protection nets. International Journal of Horticultural Science 17 (4-5), 81-85.

Lakso, A.N. and Musselman, R.C., 1976. Effects of cloudiness on interior diffuse light in apple trees. Journal of the American Society of Horticultural Science 101: 642-644.

Lakso, A.N., 1994. Environmental physiology of the apple. In: B. Schaffer and P.C. Andersen (Eds), Environmental physiology of fruit crops. Vol. 1. Temperate crops. CRC Press, Boca Raton, Florida, pp 3-42.

Lakso, A.N., 2003. Water relations of apples. In: D.C. Ferree and I.J. Warrington (Eds), Apples: Botany, production and uses. CAB International, pp 195-216.

Lakso, A.N., 2014. Comparing water use efficiency of apples and grapes – physiological and morphological aspects. Acta Horticulturae 1038: 67-72.

Lambers, H., Chapin III, F.S. and Pons, T.L., 1998. Plant physiological ecology. Springer, New York.

Landsberg, J.J. and Powell, D.B.B., 1973. Surface exchange characteristics of leaves subject to mutual interference. Agricultural Meteorology 12: 169-184.

Larcher, W., 2003. Physiological plant ecology. 4th Edition. Springer Verlag, Berlin, Heidelberg, New York.

Li, X., Yang, P., Ren, S., Li, Y., Liu, H., Du, J., Li, P., Wang, C. and Ren, L., 2010. Modelling cherry orchard evapotranspiration based on an improved dual-source model. Agricultural Water Management 98: 12-18.

Lichtenthaler, H.K., Buschmann, C., Doll, M., Fietz, H.J., Bach, T., Kozel, U., Meier, D. and Rahmsdorf, U., 1981. Photosynthetic activity, chloroplast ultrastructure, and leaf characteristics of high-light and low-light plants and of sun and shade leaves. Photosynthesis Research 2: 115-141.

Lopez, G., Boini, A., Manfrini, L., Torres-Ruiz, J.M., Pierpaoli, E., Zibordi, M., Losciale, P., Morandi, B., Corelli-Grappadelli, L., 2018. Effect of shading and water stress on light interception, physiology and yield of apple trees. Agricultural Water Management 210, 140-148.

Losciale, P., 2008. Light energy management in peach: utilization, photoprotection, photodamage and recovery. Maximizing light absorption in orchard is not always the best solution. PhD thesis. University of Bologna, Italy.

Makeredza, B., Schmeisser, M., Lötze, E. and Steyn, W.J., 2013. Water stress increases sunburn in 'Cripps' Pink' apple. HortScience 48: 444-447.

Malik, N. 2020. Shade net studies on two Japanese plum cultivars (*Prunus salicina* Lindl.). MScAgric (Horticultural Science) thesis, Stellenbosch University.

Manja, K., Aoun, M., 2019. The use of nets for tree fruit crops and their impact on the production: a review. Scientia Horticulturae 246, 110-122.

Martínez-Lüscher, J., Chen, C.C.L., Brillante, L. and Kurtural, S.K., 2017. Partial solar radiation exclusion with color shade nets reduces the degradation of organic acids and flavonoids of grape berry (*Vitis vinifera* L.). Journal of Agricultural and Food Chemistry 65: 10693−10702.

Massachi, A., Pietrini, F., Centritto, M., Loreto, F., 2000. Microclimate effects on transpiration and photosynthesis of cherry saplings growing under a shading net. Acta Horticulturae 537: 287-291.

Massonnet, C., Costes, E., Rambal, S., Dreyer, E. and Regnard, J.L., 2007. Stomatal regulation of photosynthesis in apple leaves: evidence for different water-use strategies between two cultivars. Annals of Botany, 100: 1347-1356.

McCaskill, M.R., McClymont, L., Goodwin, I., Green, S. and Partington, D.L., 2016. How hail netting reduces apple fruit surface temperature: a microclimate and modelling study. Agricultural and Forest Meteorology 226-227: 148-160.

McMahon, T.A., Peel, M.C., Lowe, L., Srikanthan, R., McVicar, T.R., 2013. Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis. Hydrol. Earth Syst. Sci. 17, 1331-1363.

Middleton, S. and McWaters, A., 2002. Hail netting of apple orchards – Australian experience. The Compact Fruit Tree 35: 51-55.

Midgley, S.J.E. and Lötze, E., 2011. Climate change in the Western Cape of South Africa: trends, projections and implications for chill unit accumulation. Acta Horticulturae 903: 1127-1134.

Midgley, S.J.E., Davis, N. and Schulze, R.E. 2021. Scientific and Practical Guide to Climate Change and Pome/Stone Fruit Production in South Africa. Extended Executive Summary. Report submitted to Hortgro Pome and Hortgro Stone, Stellenbosch, South Africa.

Midgley, S.J.E., Dzikiti, S., Volschenk, T., Zirebwa, F.S., Taylor, N.J., Gush, M.B., Lötze, E., Ntshidi, Z. and Mobe, N. 2020. Water productivity of high performing apple orchards in the winter rainfall area of South Africa. Acta Horticulturae 1281: 479-486.

Mobe, N.T., Dzikiti, S., Volschenk, T., Zirebwa, S.F., Ntshidi, Z., Midgley, S.J.E., Steyn, W.J., Lötze, E., Mpandeli, S. and Mazvimavi, D. 2020. Using sap flow data to assess variations in water use and water status of apple orchards of varying age groups in the Western Cape Province of South Africa. Water SA 46(2): 213-224.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., and Kijne, J. 2010. Improving agricultural water productivity: between optimism and caution. Agricultural Water Management 97 (4), 528-535.

Möller, M., Tanny, J., Li, Y. and Cohen, S., 2004. Measuring and predicting evapotranspiration in an insect-proof screenhouse. Agricultural and Forest Meteorology 127: 35-51.

Monteith, J.L. and Unsworth, M., 1990. Principles of environmental physics. 2nd edition. Antony Rowe Ltd, Eastbourne.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the American Society of Agricultural and Biological Engineers 50(3): 885-900.

Mupambi, G., Anthony, B.M., Layne, D.R., Musacchi, S., Serra, S., Schmidt, T. And Kalcsits, L.A., 2018. The influence of protective netting on tree physiology and fruit quality of apple: A review. Scientia Horticulturae 236: 60-72.

Naor, A. 2014. Crop Load and Irrigation Interactions – a New Dimension of RDI. Acta Horticulturae 1038: 113-119.

Naor, A., Klein, I., Doron, I., Gal, Y., Bravdo, B., Klein, I., Doron, I., Gal, Y., 1997. The effect of irrigation and crop load on stem water potential and apple fruit size. Journal of Horticultural Science 1589, 765-771.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models Part I: a discussion of principles. Journal of Hydrology 10: 282-290.

Nicolás, E., Barradas, V.L., Ortuño, M.F., Navarro, A., Torrecillas, A. and Alarcón, J.J., 2008. Environmental and stomatal control of transpiration, canopy conductance and decoupling coefficient in young lemon trees under shading net. Environmental and Experimental Botany 63: 200-206.

Nicolás, E., Torrecillas, A., Dell' Amico, J. and Alarcón, J.J., 2005. Sap flow, gas exchange and hydraulic conductance of young apricot trees growing under a shading net and different water supplies. Journal of Plant Physiology 162: 439-447.

Ntshidi, Z., Dzikiti, S. and Mazvimavi, D. 2018. Water use dynamics of young and mature apple trees planted in South African orchards: a case study of the Golden Delicious and Cripps' Pink cultivars. Proc. IAHS 378: 79-83.

Ntshidi, Z., Dzikiti, S., Mazvimavi, D., Mobe, N.T. and Mkunyana, Y.P. 2021. Water use of selected cover crop species commonly grown in South African fruit orchards and their response to drought stress. Physics and Chemistry of the Earth Parts A/B/C 124:103070. DOI:10.1016/j.pce.2021.103070.

Oguchi, R., Hikosaka, K. and Hirose, T., 2003. Does the photosynthetic light acclimation need change in leaf anatomy? Plant, Cell and Environment 26: 505-512.

Olivares-Soto, H. and Bastías, R.M., 2018. Photosynthetic efficiency of apples under protected shade nets. Chilean Journal of Agricultural Research 78: 126-138.

Ordóñez, V., Molina-Corral, F.J., Olivas-Dorantes, C.L., Jacobo-Cuéllar, J.L., González-Aguilar, G., Espino, M., Sepulveda, D. and Olivas, G.I., 2016. Comparative study of the effects of black or white hail nets on the fruit quality of 'Golden Delicious' apples. Fruits 71: 229-238.

Ortega-Farias, S. and López-Olivari, R.A., 2012. Validation of a two-layer model to estimate latent heat flux and evapotranspiration in a drip-irrigated olive orchard. Transactions of the American Society of Agricultural and Biological Engineers 55(4): 1169-1178.

Ortega-Farias, S., Lopéz-Olivari, R., Poblete-Echeverría, C., Zuñiga, M., 2012. Evaluation of a two-layer model and sap flow to estimate olive transpiration. Acta Horticulturae 951, 147-152.

Palmer, J.W., 1977. Light transmittance by apple leaves and canopies. Journal of Applied Ecology 14: 505-513.

Palmer, J.W., 1989. Canopy manipulation for optimum utilization of light. In: C.J. Wright (Ed.) Manipulation of fruiting. Butterworths, London, UK, pp 245-262.

Pitchers, B., Do, F.C., Pradal, C., Dufour, L. and Lauri, P.É., 2021. Apple tree adaptation to shade in agroforestry: an architectural approach. American Journal of Botany 108(5):732-743.

Poyatos, R., Villagarcia, L., Domingo, F., Pinol, J. and Lliorens, P., 2007. Modelling evapotranspiration in a Scots pine stand under Mediterranean mountain climate using the GLUE methodology. Agricultural and Forest Meteorology 146: 13-28.

Prins, M.d.T., 2018. The impact of shade netting on the microclimate of a citrus orchard and the tree's physiology. MSc (Horticultural Science) thesis, Stellenbosch University, Stellenbosch, South Africa.

Prokopljević, D., Stričević, R. and Miletaški, B., 2012. Effect of anti-hail nets on evapotranspiration of apple orchard in Celarevo [Serbia]. Downloaded from: http://agris.fao.org/agris-search/search.do?recordID=RS2012001793

Ramírez, F. and Davenport, T.L., 2013. Apple pollination: a review. Scientia Horticulturae, 162:188-203.

Raveh, E., Cohen, S., Raz, T., Yakir, D., Grava, A. and Goldschmidt, E., 2003. Increased growth of young citrus trees under reduced radiation load in a semi-arid climate. Journal of Experimental Botany 54: 365-373.

Rigden, P., 2008. To net or not to net. The State of Queensland, 3rd ed. Department of Primary Industries and Fisheries (Accessed 09 March 2017).

Rom, C.R., 1991. Light thresholds for apple tree canopy growth and development. HortScience, 26(8):989-992.

Romo-Chacon, A., Oroczo-Avitia, J.A., Gardea, A.A., Guerrero-Prieto, V. And Soto-Parrra, J.M., 2007. Hail net effect on photosynthetic rate and fruit color development of 'Starkrimson' apple trees. Journal of the American Pomological Society 61: 174-178.

Sakuratani, T., 1981. A heat balance method for measuring water flux in the stem of intact plants. Journal of Agricultural Meteorology 37: 9-17.

Saxton, K.E., Rawls, W.J., Romberger, J.S. and Papendick, R.I. 1986. Estimating generalized soil water characteristics from texture. Trans. ASAE 50:1031-1035.

Schulze, R.E. 2016. On observations, climate challenges, the South African agriculture sector and considerations for an adaptation handbook. In: Schulze, R.E. (Ed.) Handbook for farmers, officials and other stakeholders on adaptation to climate change in the agriculture sector within South Africa. Section A: Agriculture and climate change in South Africa: setting the scene, Chapter A1.

Shahak, Y., 2014. Photoselective netting: an overview of the concept, research and development and practical implementation in agriculture. Acta Horticulturae 1015: 155-162.

Shahak, Y., Gussakovsky, E.E., Cohen, Y., Lurie, S., Stern, R., Kfir, S., Naor, A., Atzmon, I., Doron, I. and Greenblat-Avron, Y., 2004a. ColorNets: a new approach for light manipulation in fruit trees. Acta Horticulturae 636: 609-616.

Shahak, Y., Gussakovsky, E.E., Gal, E. and Ganelevin, R., 2004b. ColorNets: crop protection and light-quality manipulation in one technology. Acta Horticulturae 659: 143-151.

Shimazaki, K.-I., Doi, M., Assman, S. and Kinoshita, T., 2007. Light regulation of stomatal movement. Annual Review of Plant Biology 58: 219-247.

Shuttleworth, W.J. and Wallace, J.S., 1985. Evaporation from sparse crops – an energy combination theory. Quarterly Journal of the Royal Meteorological Society 11: 839-855.

Simonneau, T., Habib, R., Goutouly, P. and Huguet, J.G., 1993. Diurnal changes in stem diameter changes as predictors of plant canopy water potential: direct evidence in peach trees. Journal of Experimental Botany 44: 615-621.

Smit, A., 2007. Apple tree and fruit responses to shade netting. MSc Thesis. University of Stellenbosch, Stellenbosch, South Africa.

Smit, A., Steyn, W.J. and Wand, S.J.E., 2009. Effects of shade netting on gas exchange of blushed apple cultivars. Acta Horticulturae 772: 73-80.

Soil Classification Working Group, 1991. Soil Classification – a Taxonomic System for South Africa. Memoirs on the Agricultural Natural Resources of South Africa No. 15. Department of Agricultural Development, Pretoria.

Solomakhin, A. and Blanke, M., 2008. Coloured hailnets alter light transmission, spectra and phytochrome, as well as vegetative growth, leaf chlorophyll and photosynthesis and reduce flower induction of apple. Plant Growth Regulation 56: 211-218.

Solomakhin, A. and Blanke, M., 2010a. The microclimate under coloured hailnets affects leaf and fruit temperature, leaf anatomy, vegetative and reproductive growth as well as fruit colouration in apple. Annals of Applied Biology 156: 121-136.

Solomakhin, A. and Blanke, M., 2010b. Can coloured hailnets improve taste (sugar, sugar:acid ratio), consumer appeal (colouration) and nutritional value (anthocyanin, vitamin C) of apple fruit? LWT – Food Science and Technology 43: 1277-1284.

Solomakhin, A.A. and Blanke, M.M., 2007. Overcoming adverse effects of hailnets on fruit quality and microclimate in an apple orchard. Journal of the Science of Food and Agriculture 87: 2625-2637.

Stampar, F., Hudina, M., Usenik, V., Sturm, K. and Zadravec, P., 2001. Influence of black and white nets on photosynthesis, yield and fruit quality of apple (*Malus domestica* Borkh.) Acta Horticulturae 557: 357-362.

Stamps, R.H., 2009. Use of colored shade netting in horticulture. HortScience 44, 239-241.

Stander, J. and Cronje, P.J., 2016. Important considerations for citrus production under shade nets. South African Fruit Journal 64, November 2016.

Steppe, K., Dzikiti, S., Lemeur, R. and Milford, J.R., 2006. Stomatal oscillations in orange trees under natural climatic conditions. Annals of Botany 97: 831-835.

Steyn, W.J., Holcroft, D.H., Wand, S.J.E. and Jacobs, G., 2004. Anthocyanin degradation in detached pome fruit with reference to preharvest red color loss and pigmentation patterns of blushed and fully red pears. Journal of the American Society for Horticultural Science 129: 13-19.

Szabó, A., Tamás, J., Nagy, A., 2021. The influence of hail net on the water balance and leaf pigment content of apple orchards. Scientia Horticulturae 283, 110-112.

Tanny, J. and Cohen, S., 2003. The effect of a small shade net on the properties of wind and selected boundary layer parameters above and within a citrus orchard. Biosystems Engineering 84: 57-67.

Tanny, J., Cohen, S., Grava, A., Naor, A. and Lukyanov, V., 2009. The effect of shading screens on microclimate of apple orchards. Acta Horticulturae 807: 103-108.

Tardieu, F. and Simmonneau, T., 1998. Variability among species of stomatal control under fluctuating soil water status and evaporative demand: modelling isohydric and anisohydric behaviours. Journal of Experimental Botany 49: 419-432.

Treder, W., Mika, A., Buler, Z. and Klamkowski, K., 2016. Effects of hail nets on orchard light microclimate, apple tree growth, fruiting and fruit quality. Acta Scientiarum Polonorum Hortorum Cultus 15: 17-27.

Tustin, S., Corelli-Grappadelli, L. and Ravaglia, G., 1992. Effect of previous-season and current light environments on early-season spur development and assimilate translocation in “Golden Delicious” apple. Journal of Horticultural Science 67: 351-360.

Voigt, F. and Stassen, P.J.C., 2014. The South African deciduous fruit industry’s apple rootstock scenario and current initiatives. Acta Horticulturae 1058: 465-470.

WCG (Western Cape Government), 2016. A status quo review of climate change and the agriculture sector of the Western Cape Province. Report submitted to the Western Cape Department of Agriculture and the Western Cape Department of Environmental Affairs & Development Planning. By: Midgley, S.J.E., New, M., Methner, N., et al. African Climate & Development Initiative, University of Cape Town, Cape Town.

Widmer, A., 1997. Lichtverhältnisse, Assimilation und Fruchtqualität unter Hagelnetzen. Schweizer Zeitschrift für Obst- und Weinbau 133: 197-199.

Widmer, A., 2001. Light intensity and fruit quality under hail protection nets. Acta Horticulturae 557: 421-426.

Wilkie, J.D., Sedgley, M. and Olesen, T., 2008. Regulation of floral initiation in horticultural trees. Journal of Experimental Botany, 59(12):3215-3228.

Wullschleger, S.D. and King, A.W., 2000. Radial variation in sap velocity as a function of stem diameter and sapwood thickness in yellow-poplar trees. Tree Physiology 20: 511-518.

Wünsche, J.N. and Lakso, A.N., 2000. The relationship between leaf area and light interception by spur and extension shoot leaves and apple orchard productivity. HortScience 35: 1202-1206.

Wünsche, J.N., Ferguson, I.B. and Janick, J., 2005. Crop load interactions in apple. Horticultural Reviews, 31:231-290.

Wünsche, J.N., Lakso, A.N., Robinson, T.L., Lenz, F. and Denning, S.S., 1996. The bases of productivity in apple production systems: the role of light interception by different shoot types. Journal of the American Society for Horticultural Science 121: 886-893.

Zhang, H., Wang, L., Shi, K., Shan, D., Zhu, Y., Wang, C., Bai, Y., Yan, T., Zheng, X. and Kong, J., 2019. Apple tree flowering is mediated by low level of melatonin under the regulation of seasonal light signal. Journal of Pineal Research, 66(2):12551.

APPENDIX B. CAPACITY BUILDING

Community development

Researchers and technical advisors within the pome fruit industry, and the industry in general through Hortgro Science, have been kept abreast of the results coming out of this research project through oral and written communications. There is keen interest in this community in the practical implications of the findings, from several perspectives including savings of critical water resources, more efficient and optimised irrigation practices, avoidance of negative impacts on production and fruit quality through over-irrigation, and the economic implications of the benefits at farm level. Once the summary of the project and practical guidelines are available and disseminated to these communities, farmers can take advantage of the understanding and technical options to implement appropriate practices. The project will improve the capacity of technical advisors to provide science-based guidance to growers regarding practices under shade nettings and especially irrigation management and scheduling.

Non-degree capacity building: Ms Nicole Wagner (Western Cape Department of Agriculture). Contribution to: Budget and evaluate the reduction of water costs and increase of income from apple production, in comparison with the increased capital and maintenance costs of fixed and draped netting.

Institutional development

Capacity building took place at the three collaborating institutions: Stellenbosch University, Council for Scientific and Industrial Development, and Agricultural Research Council. Researchers improved their skills in measurement techniques, e.g. sap flow monitoring and calculation of daily and seasonal tree water use, soil water content monitoring and soil water balance calculations, advanced ecophysiological measurements, crop water use modelling, and farm level financial modelling of the benefits of nets. Research managers at Hortgro Science will benefit from the availability of good science-based data on water use under nets that can be disseminated in the industry using Hortgro's various communication platforms.

Students on course for graduation

Mr E.B. Lulane – PhDAgric Horticultural Science (Stellenbosch University)

<u>Title: Quantifying the water productivity and water savings of apple orchards under fixed and draped netting.</u>

Mr Lulane is in the final stages of writing up his thesis. He will submit the thesis for examination in March 2023.

Draft thesis summary in Appendix H.

Mr S.C. Jordaan – MScAgric Horticultural Science (Stellenbosch University)

Title: The impact of protective netting on reproductive bud development, flowering, fruit set and fruit quality in apple trees

Mr Jordaan submitted his thesis for examination in December 2022 and will graduate in March 2023.

Thesis summary in Appendix I.

APPENDIX C. KNOWLEDGE DISSEMINATION & TECHNOLOGY TRANSFER

Scientific articles

Lulane, E.B., Dzikiti, S., Volschenk, T., Lötze, E., Midgley, S.J.E. (2022). Quantifying water saving benefits of fixed white protective netting in irrigated apple orchards under Mediterranean-type climate conditions in South Africa. Scientia Horticulturae 305 (2022) 111439.

Lulane, E.B., Volschenk, T., Dzikiti, S., Lötze, E., Midgley, S.J.E. (in progress) Quantifying water saving benefits of black draped nets in irrigated 'Golden Delicious' apple orchards in two Mediterranean-type climate regions of South Africa.

Lulane, E.B., Dzikiti, S., Volschenk, T., Lötze, E., Midgley, S.J.E. (in progress) Effects of fixed and draped shade nets on seasonal microclimate and leaf gas exchange of irrigated apple orchards.

Jordaan, S.C., Lötze, E., Dzikiti, S., Volschenk, T., Midgley, S.J.E. (in progress) Apple tree reproductive processes under two types of protective netting and in interaction with crop load.

Popular articles

Midgley, S., Dzikiti, S., Volschenk, T., Lötze, E. and Gush, M. (2019). Are water savings in apple orchards under shade netting an additional benefit? *South African Fruit Journal, Dec 2018-Jan 2019, pp.81-83*.

Midgley, S., Dzikiti, S., Volschenk, T., Lötze, E. and Lulane, E. (2019). Apple tree water use under shade netting. *South African Fruit Journal, Oct-Nov 2019, pp.50-52*.

Midgley, S.J.E., Lulane, E.B., Volschenk, T., Dzikiti, S. and Lötze, E. (in progress) Water savings in apple orchards under fixed white and draped black shade netting. *South African Fruit Journal*.

Midgley, S.J.E., Jordaan, S.C., Lötze, E., Dzikiti, S. and Volschenk, T. (in progress) Effects of fixed white and draped black shade netting on reproductive processes of apple orchards. *South African Fruit Journal*.

Presentations

Lulane, E.B. (2019). Quantifying the water productivity and water savings of apple orchards under fixed and draped nets. Oral. PhD Proposal Presentation, Stellenbosch University Department of Horticultural Science, 26 August 2019.

Jordaan, S.C. (2020). Quantifying the influence of protective netting on bud quality, flowering, fruit set and fruit quality in two apple cultivars. Oral. MSc Proposal Presentation, Stellenbosch University Department of Horticultural Science, 7 April 2020.

Midgley, S.J.E., Dzikiti, S., Volschenk, T., Lulane, E.B., Ntshidi, Z., Lötze, E. (2020). Investigating the potential of fixed and draped netting technology for increasing water productivity and water savings in full bearing apple orchard under micro-irrigation. Oral. Hortgro Research Showcase, 5 August 2020.

Midgley, S.J.E. (2021). Water use under nets. Oral. Hortgro Langkloof Seminar, 24 November 2021.

Midgley, S.J.E. (with acknowledgement of contributions) (2022) Water-related climate adaptation strategies for the horticultural sector in the Western Cape, South Africa. Oral. 31st International Horticultural Congress, Angers, France. Symposium 12: Water, 19 August 2022. [Includes results from this project]

Lulane, E.B., Dzikiti, S., Volschenk, T., Lötze, E., Midgley, S.J.E. (2023) A study of two types of protective nets on the microclimate and the water use of apple orchards in South Africa. Poster. Xth International Symposium on Irrigation of Horticultural Crops, Stellenbosch, February 2023.

Midgley, S.J.E., Lulane, E.B., Volschenk, T., Dzikiti, S. and Lötze, E. (planned) Water savings in apple orchards under fixed white and draped black shade netting. Hortgro event.

Midgley, S.J.E., Jordaan, S.C., Lötze, E. and Dzikiti, S. (planned) Effects of fixed white and draped black shade netting on reproductive processes of apple orchards. Hortgro event.

Technology transfer to industry

The project has delivered two popular publications in the *SA Fruit Journal*. Two presentations were made at industry events: the Hortgro Research Showcase in 2020, and the Hortgro Langkloof Seminar in 2021. The Hortgro Irrigation and Nutrition Workgroup has included the project in the agenda for its annual meetings in 2019, 2020, 2021 and 2022.

The final deliverable is the “Practical illustrative guide on the potential water savings achievable with netting of full bearing apple orchards” which summarises the research findings in ca. 20 pages and is written in a grower-friendly style. This will be disseminated within the industry once it has been approved by WRC and Hortgro Science.

APPENDIX D. Cross calibration of weather station sensors before measurements at the fixed and draped nets sites, 2019

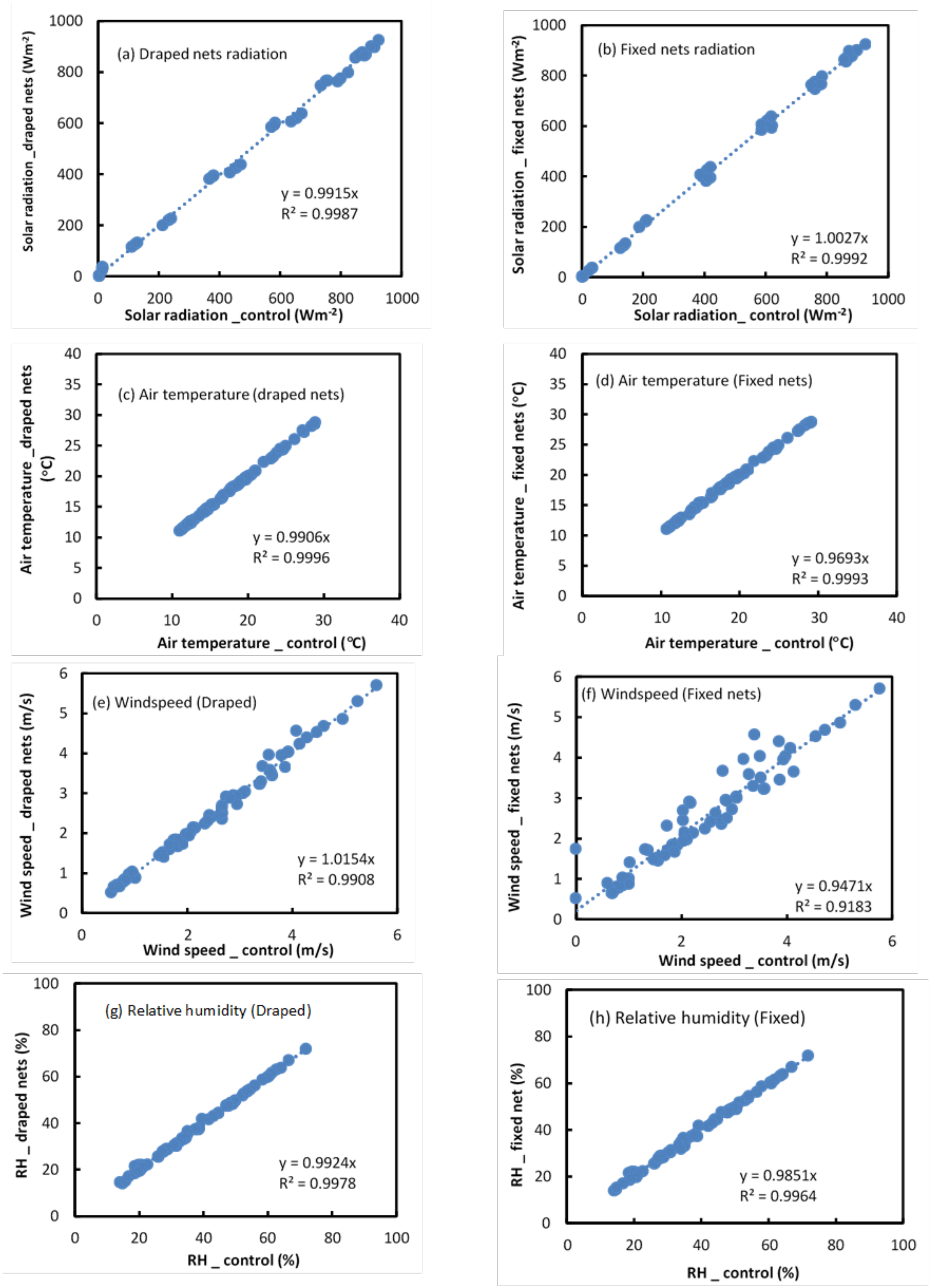


Figure 136 Calibration comparison of the (a) solar radiation, (c) air temperature, (e) wind speed, and (g) relative humidity of the weather station deployed under the draped nets with that in the control treatment. Figures (b), (d), (f) and (h) represents the climate variables for the fixed nets weather station. Data was collected from 26-29 September 2019.

APPENDIX E. Installation of soil water monitoring equipment

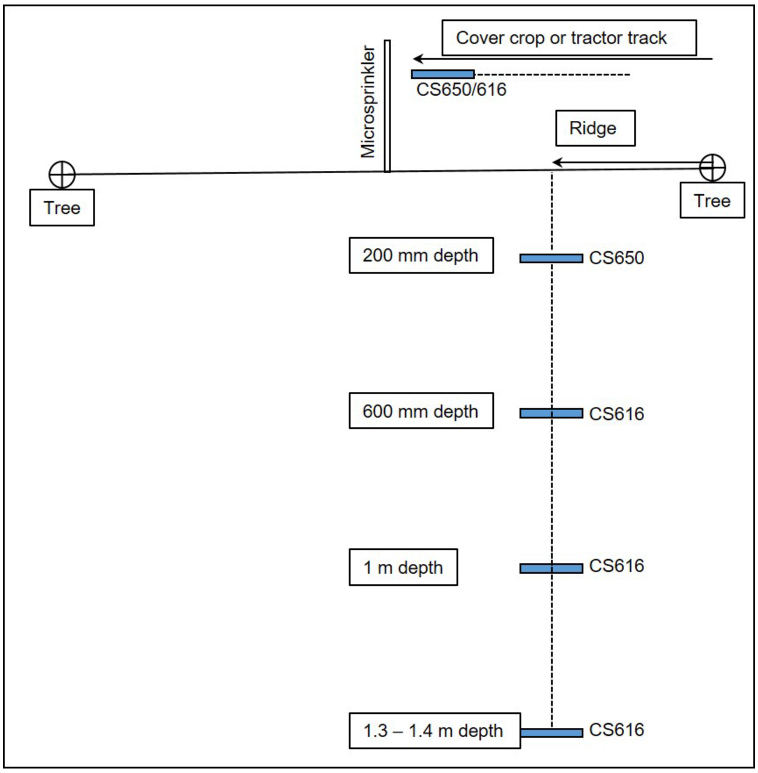


Figure 137 Illustration of the position and depths of the CS650 and/ or CS616 sensors installed in the ridge, tractor track or cover crop relative to the tree (encircled cross) in the 'Rosy Glow' and 'Golden Delicious Reinders' orchards at Paardekloof. Sensors in the ridge were installed across the ridge.

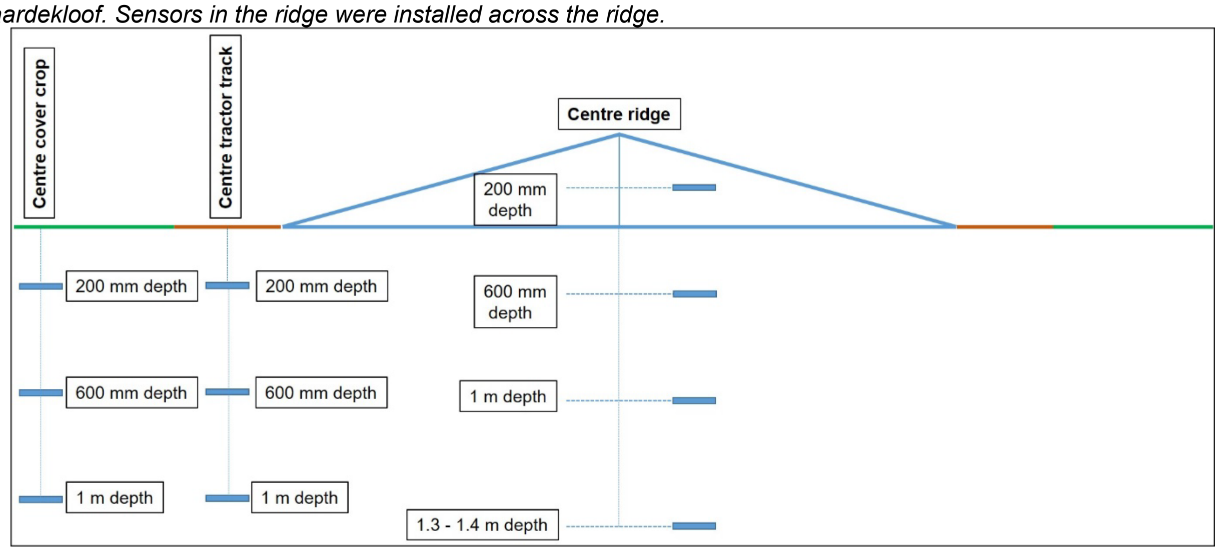


Figure 138 Illustration of the position and depths of the CS650 and/ or CS616 sensors (blue blocks) installed in soil relative to ridged 'Rosy Glow' and 'Golden Delicious Reinders' trees at Paardekloof.

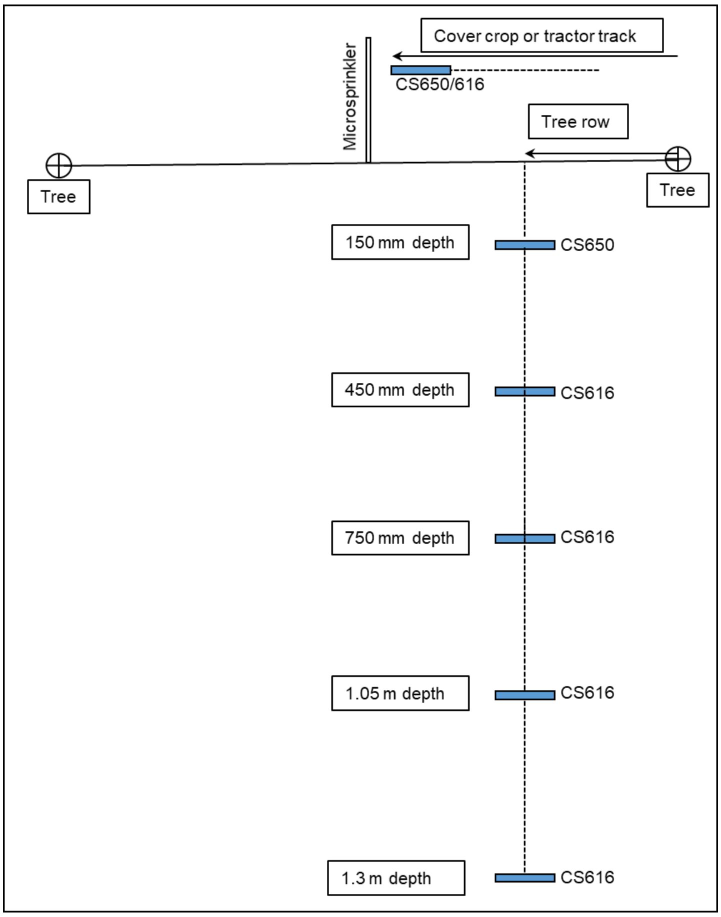


Figure 139 Illustration of the position and depths of the CS650 and CS616 sensors installed in the centre tree row, tractor track or cover crop relative to the tree (encircled cross) below the open and draped net sections in the 'Golden Delicious' orchard at Southfield in 2020. Sensors in the tree row were installed across the centre tree row.

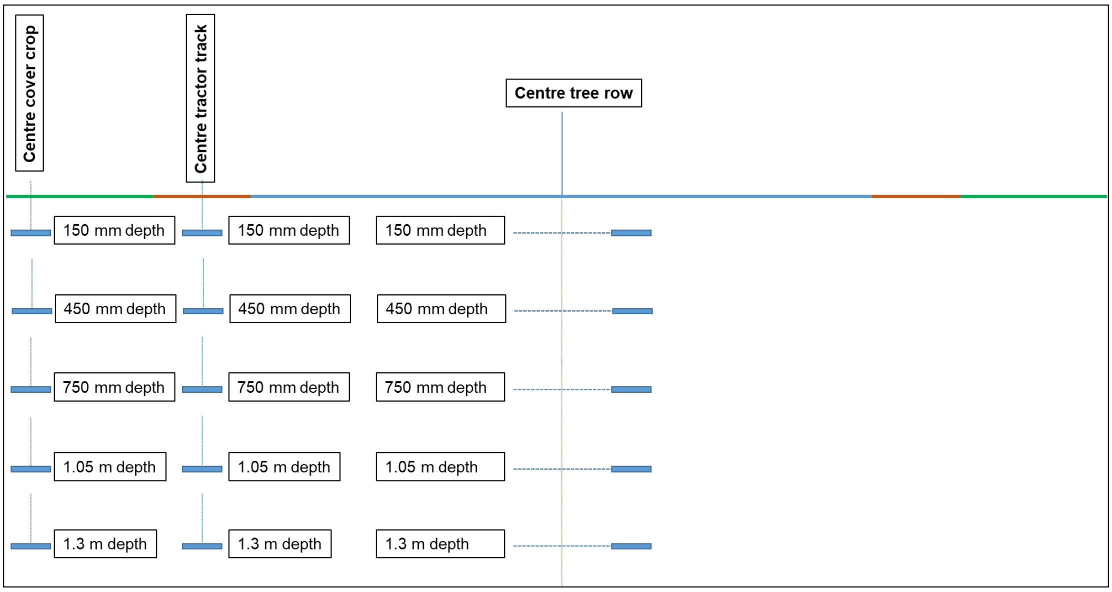


Figure 140 Illustration of the position and depths of the CS650 and CS616 sensors (blue blocks) installed in soil relative to the 'Golden Delicious' trees at Southfield in 2020.

APPENDIX F. Calibration of soil moisture sensors

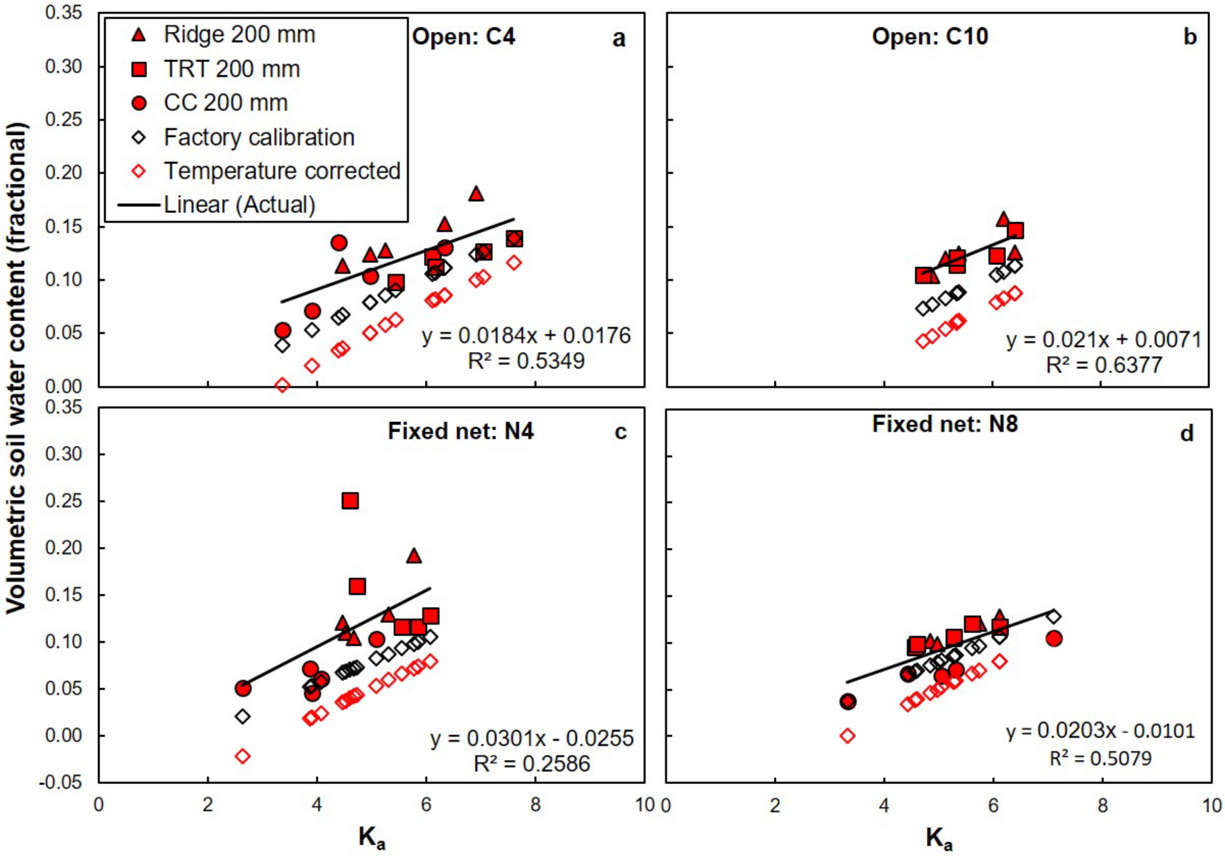


Figure 141 Comparison of gravimetrically sampled volumetric soil water content (filled red symbols) as well as original and temperature corrected factory calibrated volumetric soil water content of CS650 soil water content sensors (empty black and red diamonds, respectively) to the bulk dielectric permittivity of the soil (Ka) . Gravimetric samples were taken at the 200 mm depth in the ridge, tractor track (TRT) and cover crop (CC) areas of the 'Rosy Glow' orchard during 2018-2019 and 2019-2020.

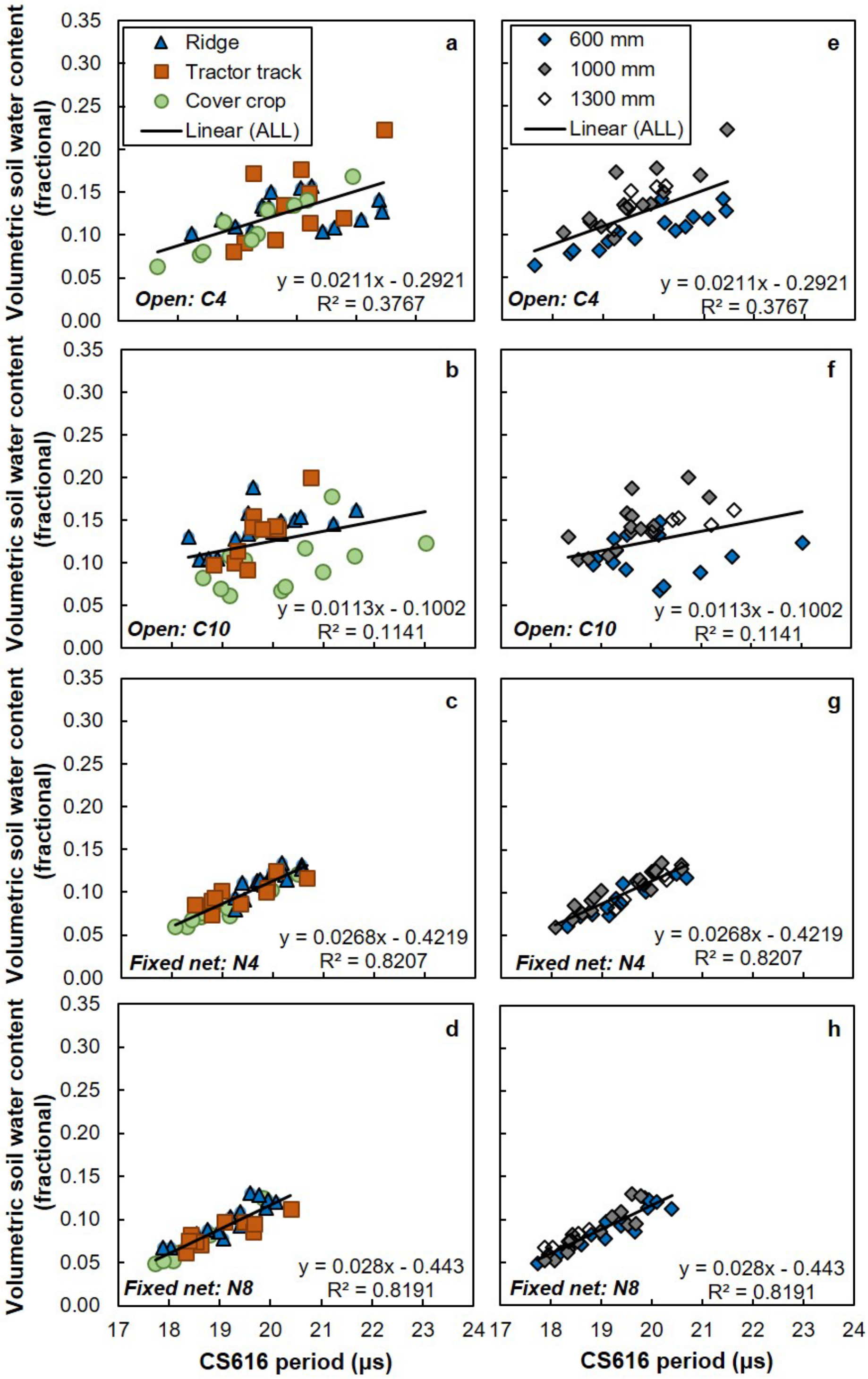


Figure 142 Comparison of gravimetrically sampled volumetric soil water content to the CS616 soil water content sensor period (µs) for orchard areas combined (a-d) and over measurement depths (e-h) per soil water balance site (C4, C10, N4, N8) for the open (a, b, e, f) and fixed net (c, d, g, h) sections of the 'Rosy Glow' orchard during 2018-2019 and 2019-2020.

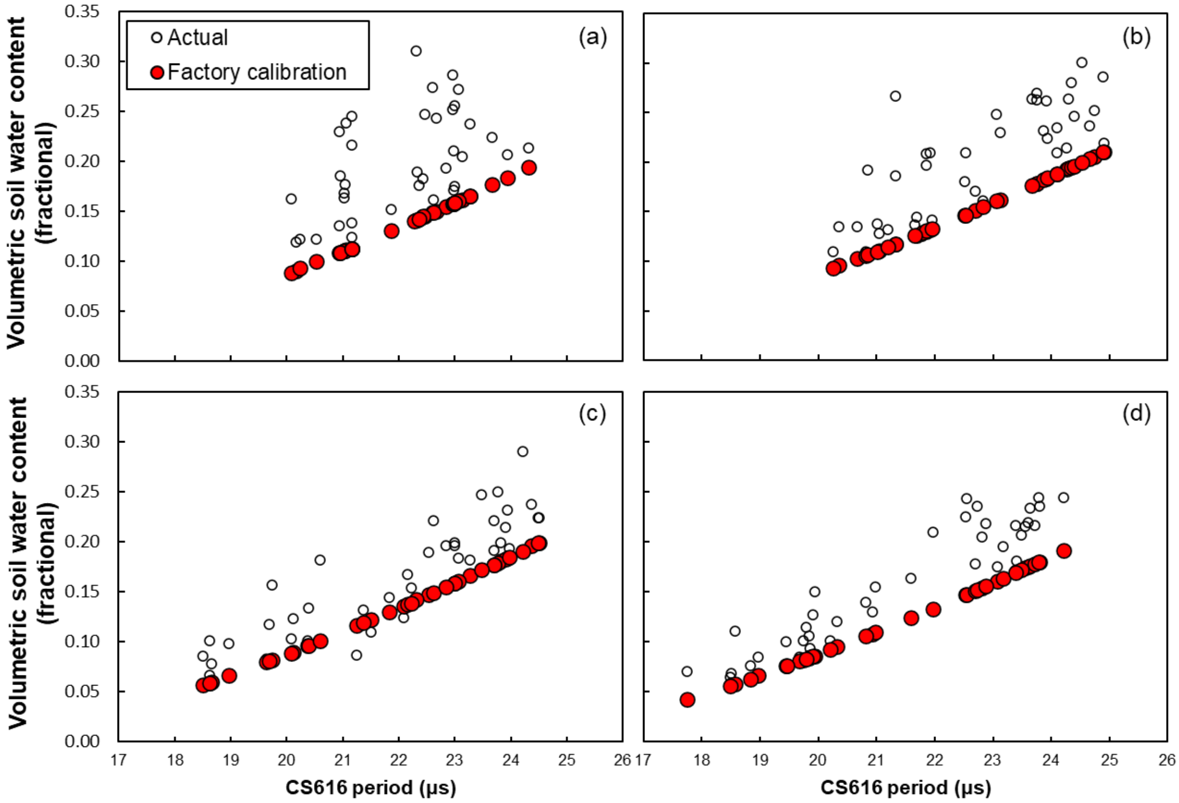


Figure 143 Comparison of CS616 factory calibrated soil water content and actual volumetric soil water content sampled simultaneously for various CS616 periods at the control treatment soil water balance replicate 1 (a) and 2 (b) and for the draped net soil water balance replicate 1 (c) and 2 (d) in the 'Golden Delicious Reinders' orchard at Paardekloof.

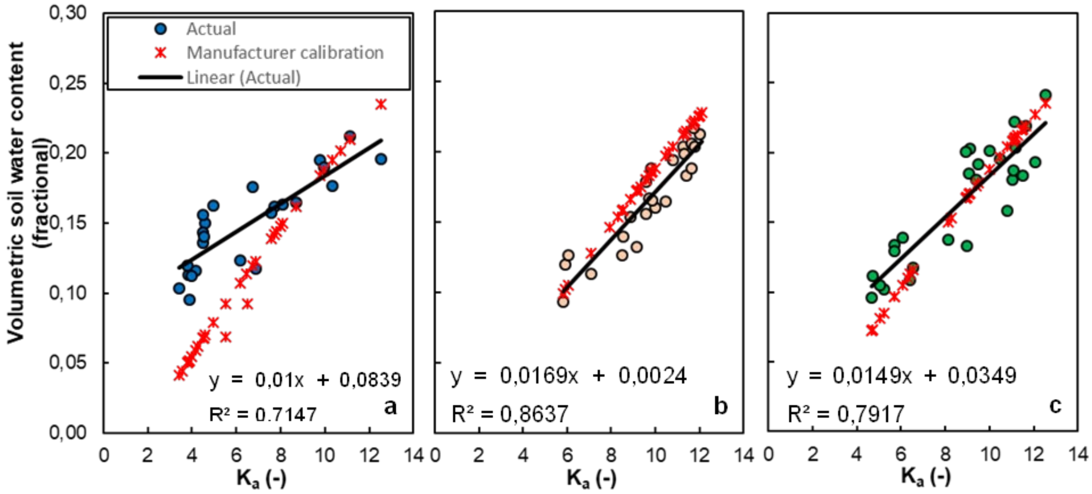


Figure 144 Comparison of CS650 manufacturer calibrated soil water content and actual volumetric soil water content sampled simultaneously at the 150 mm depth at various dielectric permittivities for the tree row (a, n=24), tractor track (b, n= 24) and cover crop areas (c, n=27). Data were combined for all four soil water balance installations.

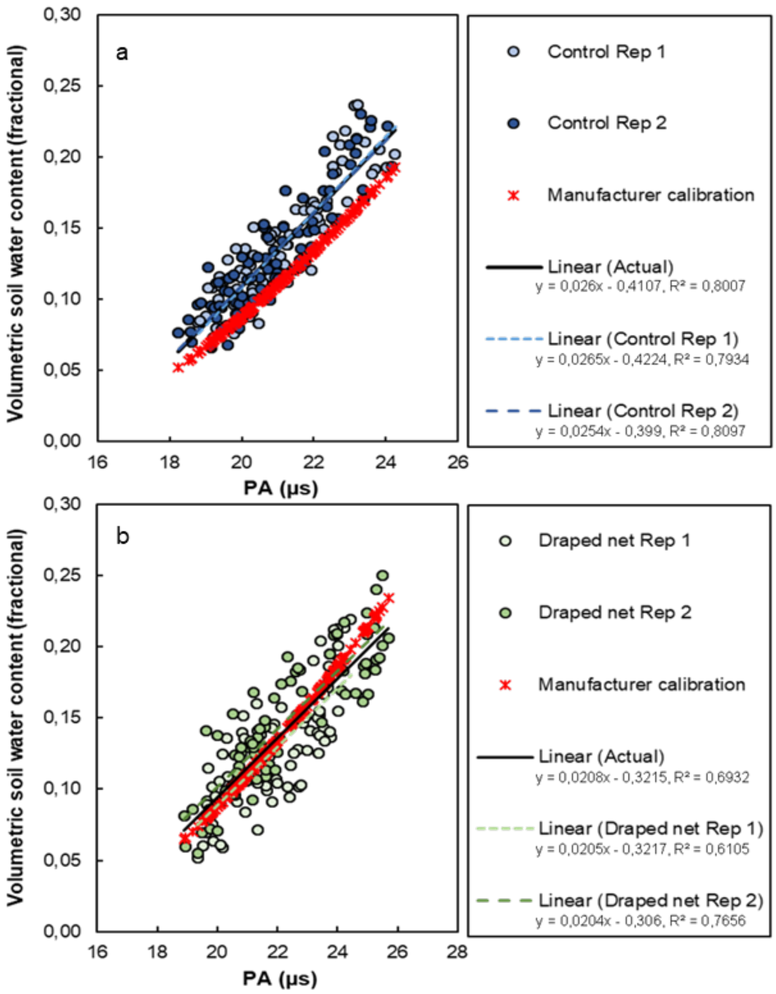


Figure 145 Comparison of CS616 factory calibrated soil water content and actual volumetric soil water content sampled simultaneously at various CS616 periods at (a) soil water balance replicate 1 and 2 for the control treatment (n=170) and (b) soil water balance replicate 1 and 2 for the draped net treatment (n=162).

Table 53 Summary of linear regression statistics of gravimetrically sampled volumetric soil water content vs CS650 dielectric permittivity (Ka) or CS616 period of sensors installed in three different orchard areas at the 'Rosy Glow' orchard, Paardekloof. Data for depths (220, 600, 1000, 1300 mm) and/or orchard areas (Ridge/R; Tractor track/ TRT; Cover crop/ CC) were pooled where feasible. SWB1 and SWB2 are fixed net and SWB3 and SWB4 control soil water balance replicates.

ID	Position	X-coeff	Intercept	R^2 %	p-value	Estimate SE	MAE	n	Period/Ka Min	Range Max
SWB1	D200	0.021	0.005	85.0	<0.0001	0.009	0.007	12	2.6	6.1
	D600_1300	0.027	-0.427	83.4	<0.0001	0.009	0.008	39	17.8	20.7
SWB2	R&TRT200	0.021	-0.001	90.3	<0.0001	0.004	0.003	10	4.6	6.1
	CC200	0.017	-0.017	95.5	0.004	0.006	0.004	5	3.3	7.1
	D600&1300	0.029	-0.46	87.2	<0.0001	0.009	0.007	39	17.0	20.4
SWB3	R200	0.027	-0.01	96.5	0.003	0.006	0.004	5	4.5	6.9
	TRT200	0.019	-0.003	99.5	<0.0001	0.001	0.001	5	5.4	7.6
	CC200	0.025	-0.023	98.5	0.001	0.005	0.004	5	2.5	6.3
	D600	0.018	-0.248	95.8	<0.0001	0.005	0.004	15	17.4	21.4
	D1000&1300	0.026	-0.377	91.4	<0.0001	0.006	0.005	16	18.2	20.9
SWB4	R&TRT200	0.025	-0.014	93.6	<0.0001	0.004	0.003	9	4.7	6.4
	CC200	0.017	-0.23	98.1	0.009	0.004	0.002	4	17.4	20.6
	R&TRT600	0.028	-0.423	78.4	0.002	0.008	0.007	9	18.8	20.2
	CC600	0.018	-0.294	98.9	0.001	0.003	0.002	5	20.2	23.0
	R&TRT1000	0.04	-0.644	82.4	<0.0001	0.014	0.011	10	18.5	20.8
	CC1000	0.037	-0.603	94.7	0.001	0.009	0.006	6	18.5	21.2
	R1300	0.015	-0.16	80.5	0.015	0.007	0.005	6	19.1	21.7

Table 54 Summary of linear regression statistics of gravimetrically sampled volumetric soil water content vs CS616 period of sensors installed in three different orchard areas at the 'Golden Delicious Reinders' orchard, Paardekloof. Data for depths (200, 600, 1000, 1300/1400 mm) and/or orchard areas (Ridge/R; Tractor track/ TRT; Cover crop/ CC) were pooled where feasible. SWB1 and SWB2 are control and SWB3 and SWB4 draped net soil water balance replicates.

ID	Position	X-coeff	Intercept	R^2 %	p-value	Estimate SE	MAE	n	Period/Ka Min	Range Max
SWB1	ALL	0.023	-0.343	74.6	<0.0001	0.017	0.013	23	20.2	24.3
SWB2	R200	0.03	-0.459	78.8	<0.0001	0.023	0.019	14	20.4	24.3
	R600	0.033	-0.513	98.1	0.0098	0.007	0.005	4	21.3	23.9
	R1000	0.033	-0.553	95.3	0.0239	0.018	0.013	4	20.4	24.3
	R1300	0.034	-0.587	93.9	0.0312	0.015	0.009	4	21.0	23.9
	TRT200[1]	0.033	-0.517	81.4	0.0001	0.019	0.014	11	20.7	24.4
	TRT600	0.028	-0.465	99.4	0.0031	0.006	0.004	4	20.3	24.7
	TRT1000[2]	0.034	-0.588	84.1	0.0001	0.025	0.019	11	20.4	24.9
	CC20	0.038	-0.649	94.0	0.0303	0.016	0.009	4	20.7	23.8
	CC60	0.034	-0.586	98.1	0.0096	0.011	0.007	4	20.8	24.7
	CC1000[2]	0.034	-0.588	84.1	0.0001	0.025	0.019	11	20.4	24.9
SWB3	ALL	0.025	-0.386	93.7	<0.0001	0.014	0.012	30	18.5	24.5
SWB4	ALL	0.029	-0.461	90.9	<0.0001	0.018	0.014	38	17.7	24.2

1 Orchard areas pooled for 200 mm depth

2 Orchard areas pooled for 1000 mm depth

APPENDIX G. Soil particle size

Table 55 Texture class and particle size analysis for different soil depth increments of the soils sampled below fixed net and in the open (Control) at Paardekloof in 2018.

Treatment	Depth increment (mm)	Texture class	Clay (%)	Silt (%)	Sand Fine	Medium (%)	Coarse	Stone (v/v)
Open (Control)	0-300	Sand	5	4.0	36.6	22.4	32	0.4
	300-600	Sand	5	2.0	36.4	22.0	34.6	0.3
	600-900	Sand	5	4.0	39.4	21.2	30.4	1.2
	900-1200	Sand	5	4.0	35.6	20.0	35.4	1.7
Under net	0-300	Sand	5	4.0	42.9	28.4	19.7	2
	300-600	Sand	5	2.0	40.6	27.6	24.8	1.5
	600-900	Sand	5	2.0	37	27.0	29	0
	900-1200	Sand	5	2.0	33.2	24.8	35	1.4

Table 56 Texture class and particle size analysis for different soil depth increments of the soils sampled below draped net and in the open (Control) at the 'Golden Delicious Reinders' orchard at Paardekloof in 2019.

Treatment	Depth increment (mm)	Texture class	Clay (%)	Silt (%)	Sand Fine	Medium (%)	Coarse	Stone (v/v)
Open (Control)	0-300	Sand loam	5	10	61.4	6.8	16.8	0.2
	300-600	Loam sand	5	8	59.4	7.2	20.4	0.4
	600-900	Loam sand	5	8	64.4	6.2	16.4	0.1
	900-1200	Sand loam	9	8	47	8.4	27.6	0.3
Below net	0-300	Loam sand	11	8	47	7.2	26.8	3.3
	300-600	Loam sand	5	12	55.3	6.3	21.4	0.1
	600-900	Loam sand	7	10	54.4	6.6	22	0.2
	900-1200	Loam sand	11	8	54.1	8.3	18.6	2.2

Table 57 Texture class and particle size analysis for different soil depth increments of the soils sampled below draped net and in the open (Control) at the 'Golden Delicious' orchard at Southfield in 2020. The soil contained no stones.

Treatment	Depth increment (mm)	Texture class	Clay (%)	Silt (%)	Sand Fine	Medium (%)	Coarse
Open (Control)	0-300	Sandy loam	14	10	23.4	36	16.6
	300-600	Sandy loam	18	8	19.2	36.6	18.2
	600-900	Sandy loam	16	6	17.4	37.2	23.4
	900-1200	Loam coarse sand	10	4	18.4	41.4	26.2
Below net	0-300	Sandy loam	16	8	26.4	32.6	17.0
	300-600	Sandy loam	18	10	22.9	34.3	14.9
	600-900	Sandy loam	18	10	19.4	36.0	16.6
	900-1200	Sandy loam	10	2	20.8	45.6	21.6

APPENDIX H. PhD Thesis Summary (E.B. Lulane)

Contributions to this report:

Report Section	Contribution
Orchard microclimate	**Large**
Soil properties, soil water content and irrigation	**Medium**
Tree growth and leaf area index	**Large**
Water potential, gas exchange and WUE	**Large**
Tree transpiration and orchard floor evaporation	**Medium**
Orchard evapotranspiration – soil water balance	**Medium**
Yield, fruit maturity and fruit quality	Small
Water productivity	**Large**
Modelling water use of open and netted orchards	**Medium**
Budgeting lifetime costs and income	None

SUMMARY OF FIRST SECTION:

Apple (*Malus domestica* Borkh.) producers are increasingly using nets to address climate and pest-related challenges. In the water-scarce Western Cape region of South Africa, all commercial apple orchards are irrigated. Based on limited information on tree water relations under protective nets, we hypothesised that significant water savings and improvements in crop water productivity could be achieved under nets. The lack of accurate quantitative information on water use under nets may perpetuate sub-optimal irrigation practices partly due to inaccurate crop coefficients.

This study quantified tree transpiration (T) using the heat ratio sap flow method and orchard evapotranspiration (ET) using the soil water balance approach in mature irrigated 'Rosy Glow' apple orchards under fixed white net compared to an open (control) over two seasons. Differences in water use between treatments were analysed by comparing microclimates, plant water status, root zone soil moisture, and irrigation levels. Averaged over the two seasons, the nets reduced daily total solar radiation by ~ 12%, wind speed by more than 36%, and reference evapotranspiration by ~ 12%. Seasonal T was 11% lower under nets, while ET was only 4% lower. The nets reduced irrigation water requirement by 4%.

Peak mid-season basal crop coefficients (K_{cb}) were 0.54±0.02 and 0.59±0.02 while there were no differences in the single crop coefficients (K_c = 1.07±0.04 and 1.13±0.06) for the nets and control treatments, respectively. Transpiration based crop water productivity (WP) was higher under nets (20.7 kg m^{-3}) compared to 18.2 kg m^{-3} in the open. There were no differences in the ET-based WP values (13.4 and 13.2 kg m^{-3}) for the nets and control treatments, respectively. This study suggests that water saving benefits of fixed nets are smaller than expected when considering ET rates because of more active ground cover under nets. But there is merit in adjusting crop coefficients for irrigation scheduling under nets given the much lower transpiration.

APPENDIX I. MSc Thesis Summary (S.C. Jordaan)

Contributions to this report:

Report Section	Contribution
Orchard microclimate	Small
Soil properties, soil water content and irrigation	None
Tree growth and leaf area index	**Large**
Water potential, gas exchange and WUE	None
Tree transpiration and orchard floor evaporation	None
Orchard evapotranspiration – soil water balance	None
Yield, fruit maturity and fruit quality	**Large**
Water productivity	None
Modelling water use of open and netted orchards	None
Budgeting lifetime costs and income	None

SUMMARY

The overall objective of this study was to determine how yield, fruit quality and maturity, reproductive bud development, flowering, fruit set and early fruit growth of apple orchards are impacted by two types of protective netting compared to open orchards, in the Western Cape Province of South Africa. The study also aimed to investigate the interactive effects between black draped netting and various levels of crop load on reproductive processes of 'Golden Delicious' trees. To achieve these aims, three trials were conducted over two seasons.

In the first trial, fixed white (20%) netting over 'Rosy Glow' resulted in improved fruit growth rate, increased fruit diameter and mass, lighter green ground colour, less peel red colour, lower viable seed count, and less sunburn and hail damage in two consecutive seasons. The netting did not induce any significant effect on percentage reproductive buds (R-buds), R-bud progression for different shoot types, flower progression, flower quality, and early fruit growth. A small but significant reduction in fruit set percentage under netting was, however, found.

In the second trial, black draped netting (end-November to end-February) over 'Golden Delicious Reinders' resulted in greener fruit, less sunburn and hail damage, reduced firmness, and reduced ratio of total soluble solids (TSS) to titratable acidity (TA). R-bud percentage was promoted under the netting; however, R-bud progression was delayed after net removal. The latter effect may have culminated in delayed flowering, lowered fruit set (farm data) and reduced early fruit growth.

In the third trial, black draped netting (mid-December to early March) over 'Golden Delicious' resulted in more stem-end russet, greener ground colour, lower firmness and advanced starch breakdown, fewer viable seed, less sunburn, and lower TSS and TA. Significant interactions between net/control and crop load treatments were found for ground colour, TA and TSS:TA. R-bud percentage was higher and more uniform across all crop loads and shoot types under the netting,

while the control treatment displayed an increasing R-bud percentage for decreasing crop load level across most shoot types. After the harvest and net removal, R-bud progression was slightly but significantly delayed. Flower progression was unaffected by the netting. For flower quality, significant interaction between flower type and netting was found for pedicel length, receptacle length and number of locules. In addition, significant interaction between net/control and crop load treatments was found for ovule length. Fruit set percentage improved under netting. The different crop load levels did not have a significant impact on flower progression, flower quality and fruit set.

The use of both fixed and draped netting in apple orchards has the potential to improve apple fruit quality. However, caution is required based on the impact of draped netting on flowering and reproductive growth during the following season in ‘Golden Delicious’ and its strains. Crop load adjustments are recommended in ‘Golden Delicious’ and its strains to minimise the impact of netting on reproductive growth during the current and following season.