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Research Paper

Novel approach to evaluate the dynamic variation of wind drift and evaporation losses under moving irrigation systems

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The increased need for water and food security requires the development of new approaches to save water through irrigation management strategies, particularly for center pivot irrigation. To do so entails monitoring of the dynamic variation in wind drift and evaporation losses (WDELs) of irrigation systems under different weather conditions and for relatively long time periods. The historical catch can method has limited our ability to address this goal. Here, a new and easy-to implement methodology, called the strip test, was developed and validated against the catch can technique. Our results showed strong agreement between the catch can method and the strip test for determining the average water application efficiency (WAE ≈ 1-WDEL). Because the strip test method was measured for shorter intervals compared to the catch can method, the variables influencing WAE were able to be compared during each test. WAE had a large variance over time, which was controlled, in part, by wind speed (>4 m s^{-1}). Site-specific characterisation of WDEL is needed to apply this technique. Once applied, it can provide a better understanding of WAE behaviour over the time, and enhance the capability of predicting results for the optimising water use in sprinkler irrigation.

1. Introduction

In many areas of the world, 70–80 % of available fresh water is currently used in agriculture (Hoekstra & Chapagain, 2007). However, it is expected that as population and economy grow, a larger fraction of available water will be required for non-agricultural purposes, e.g., urban and industrial applications (Boserup, 2005). Also, climate change has already limited water resources for many regions of the world (Bandyopadhayay, Bhadra, Raghuwanshi, & Singh, 2009; Li et al. 2007; McVicar et al., 2007), which has a negative feedback to future agricultural sustainability and food security (Gheysari et al., 2015; Rockström et al., 2009). Optimising

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Nomenclature

T	Temperature (°C)
j	An index representing the tip number within each 5-min interval
WAE	water application efficiency
L	total distance between the first and the last row of cans (m)
WDEL	wind drift and evaporation loss
m	the total number of tips over 5-min for strips B
WAE_{can}	WAE from the catch can method
n	the total number of tips over 5-min for strips A
WAE_{Strip}	WAE from the strip method
p	the total number of tips over 5-min for strips C
z_i	The catch can irrigation depth after taking evaporation into account (m)
q_{av}	average sprinkler discharge (m^3 min^{-1})
α	Tipping bucket calibration coefficient
$q_{A,j}$	the flow rate for strips A after the j^{th} tip (m^3 min^{-1})
β	Strip width (m)
$q_{B,j}$	the flow rate for strips B after the j^{th} tip (m^3 min^{-1})
Δt	time difference between two consecutive tips
$q_{C,j}$	the flow rate for strips C after the j^{th} tip (m^3 min^{-1})
λ	sprinkler head spacing (m)
RH	relative humidity

agronomic water use efficiency through new irrigation management approaches is one way to mitigate this negative feedback, while at the same time, maximizing economic returns (Delirhasannia, Sadraddini, Nazemi, Farsadizadeh, & Playán, 2010; Evans & Sadler, 2008; Montazar & Behbahani, 2007).

Center pivot irrigation systems currently irrigate more than 12.5 million ha around the globe (Spears, 2003; Sadeghi & Peters, 2013), and they are steadily replacing traditional flood irrigation and other types of sprinkler irrigation. The key advantage of center pivots is their ability to apply water on a regular and consistent basis (Peters & Evett, 2007). In addition, pivots can easily irrigate large fields with relatively low labour and energy costs, and they are also adaptable to different and changing management objectives (Keller & Bliesner, 1990; Kincaid, Salomon, & Oliphant, 1996). Despite these advantages, center pivot systems are unable to irrigate the whole circle in a perfectly uniform manner. The 'global' water application uniformity is dependent on the water application efficiency (WAE), *i.e.*, the amount of water that reaches the soil surface for storage divided by the amount of water that leaves the sprinkler nozzles for any given area (Harrison, 1993; ANSI 1995). It is generally recognised that typical center pivots will have an average WAE of 80–85% (Musick, Pringle, & Walker, 1988; Neibling, Shewmaker, & Falen, 2009). The temporal WAE is, however, not necessarily within this range and mostly depends on wind drift and evaporation losses (WDELs, where WAE ≈ 1-WDELs), *i.e.*, spray losses (Ortiz, Tarjuelo, & Juan, 2009; Schneider, 2000) that occur during the irrigation event. The most rapid center pivots complete a full rotation in ~1½ days, but 2-to-4 days per rotation is typical. Over this time period a wide range in weather (synoptic), diurnal, and microclimate conditions occurs. On a large scale, this contributes to poor application uniformity under center pivots, as well as inaccurate estimates of actual water application depths. A grower using an irrigation system with inconsistent uniformity must then apply additional water in order to adequately irrigate the entire field, often applying water when and where it is not needed. Overwatering some areas increases the risk of potential runoff, nutrient leaching and soil loss (Bauder, Andales, & Waskom, 2008; Santos, Reis, Martins, Castanheira, & Serralheiro, 2003). Non-uniform watering will also result in non-uniform plant growth reducing overall yield and producing a loss of quality (Ortiz, Juan, & Tarjuelo, 2010).

Finding practical solutions to reduce the temporal variation in center pivot water application efficiency is clearly needed. Catch-can based studies have been conducted in the past to measure the WAE of pressurised irrigation systems (Abo-Ghobar, 1992; Bavi, Kashkuli, Boroomand, Naseri, & Albaji, 2009; Christiansen, 1942; Faci, Salvador, Playán, & Sourell, 2001; Frost & Schwalen, 1955; George, 1955; King, Dungan, & Bjorneberg, 2012; Kohl, Kohl, & DeBoer, 1987; Kraus, 1966; McLean, Ranjan, & Klassen, 2000; Musick et al., 1988; Ocampo, Thomas, Hook, & Harrison, 2003; Ortiz et al., 2009; Playán et al., 2005; Robinson, 1973; Seginer, Kantz, & Nir, 1991; Silva, 2006; Sternburg, 1967; Tarjuelo, Montero, Carrion, Honrubia, & Calvo, 1999; Yazar, 1984). The testing usually involved the placement of multiple catch cans in a networked pattern and estimating the amount of water being delivered to the cans (assuming spatial independence of the measurements, Loescher, Powers, & Oberbauer, 2002). Although the catch-can test is a standardised international test (ISO 11545) that is quick and suitable for discretely evaluating system performance during the growing season, it cannot be used to measure the continuous variation of the WAE due to (i) its lack of spatial representation, *i.e.*, n-size sampling theory (Loescher, Ayres, Duffy, Luo, & Brunke, 2014), (ii) its inability to reflect the dynamic variation of WAE, *i.e.*, more than 30-min is needed and only a single data point is provided at the end of the experiment, (iii) low catch efficiency occuring under windy conditions (Hendawi, Molle, Folton, & Granier, 2005; Kohl, 1972; Livingston, Loftis, & Duke, 1985; Marek, Schneider, Baker, & Popham, 1985) and; (iv) it is a cumbersome and time-consuming technique (Sadeghi & Peters, 2012; Uddin, Smith, Hancock, & Foley, 2010). For example, recent catch can based studies carried out by Playán et al. (2005) and Ortiz et al. (2009) used only 52 and 47 irrigation tests to evaluate WDELs under a center pivot irrigation.

Optimising irrigation WAE requires a new approach to advance our understanding of the abiotic controls on the continuous variation of WDELs under different weather conditions. As such, estimates of WAE (and subsequently WDELs) must be determined over both short- and long-sampling periods that span the microclimate (5–60-min) diurnal (24-h), and synoptic (several days) controls. Using a larger catchment area can also be measured more frequently and be a possible solution to achieve this goal, *i.e.*, collector strips. This method has been previously used to evaluate the uniformity of spray distribution from nozzles in laboratory conditions (rf. Sayinci & Bastaban, 2011) as well as estimating surface runoff and/or

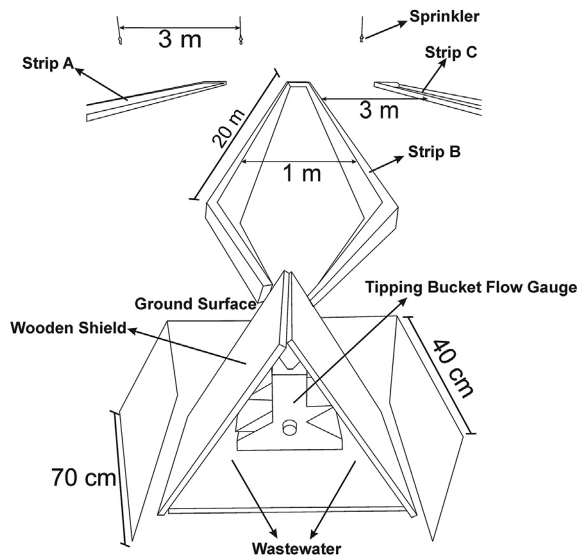

Fig. 1 – Conceptual representation of a strip and its tipping bucket.

sediment on different soil textures (rf. Sharpley, 1995; Ghadiri, Rose, & Hogarth, 2001). However, to date, no effort has been made to use this technique for measuring the WAE under irrigation systems. Here, we propose, develop and validate the strip method as a cost effective technique to monitor WAE under different weather conditions for center pivot and linear move irrigation systems.

2. Materials and method

We used a two-span stationary linear move irrigation system located at the Irrigated Agricultural Research and Extension Center (IAREC), Washington State University, Prosser, WA, USA (46° 15′ 6.40″ N, 119° 44′ 21.64″ W, 351 m a.s.l). Each span was 60 m long and consisted of twenty sprinklers installed at a 3 m spacing and 1.5 m a.g.l. Sprinklers were six-groove spinner yellow plate spray (model S3000, Nelson Irrigation Corp., Walla Walla, WA, USA), and were equipped with 103.42 KPa pressure regulators and 4.37 mm diameter nozzles (#22, Nelson Irrigation Corp). The nozzle flow rate was characterised before this study as 13 l min^{-1} from measures of discharged volume and irrigation time.

To capture the amount of water being delivered to the soil surface, three small surface runoff catchments (*i.e.*, referred to as strips, 21 m × 1 m × 0.1 m) were made from a wooden berm, impervious tarp on the soil, and a sub-surface mounted tipping bucket rain gauge (TB1L; Hydrological Services Pty Ltd, Australia) (Fig. 1). These strips were placed underneath- and perpendicular-to the lateral movement of the linear irrigation system (see A, B and C in Fig. 2). Preliminary characterisation of the sprinklers determined a maximum wetted radius of 10 m under very windy conditions (~6 m s^{-1}). Because the linear system was stationary and positioned at the center of the collection strips, the 21 m span length was therefore assumed to be a representative area. PVC pipes (25 mm diameter) were attached to the top of each berm so that catchment surface area was well defined (*i.e.*, 21 m^2). The soil was bare with a slope of 0.1% (Nakawuka, Okwany, Peters, Desta, & Sadeghi, 2014).

Because the prevailing wind direction for the area under study was SW to NE, we positioned the strips to capture the full (not partial) effect of the prevailing winds. Hence, the strips were placed in the middle of the left span and close to the middle tower (Fig. 2), which also minimised the effect of edge sprinklers underestimating WDELs. It should be noted that the 20 sprinklers on the right span were not used during this study to avoid additional runoff not contributed by our experimental design. We also objectively chose the placement of the strips to assure spatial representation (*i.e.,* effect of the catchment location) of the WDELs in relation to the distance from the sprinklers, *i.e.*, the right berm of strip C was located exactly beneath the 6th sprinkler whereas those of strips B, and A were 1 m and 2 m away from the 7th, and the 8th sprinkler, respectively (Fig. 2). The strips were installed by gently levelling the soils to remove any depressions from the surface.

The berms were made of wood and were funnelled downstream such that the runoff was oriented toward the outlet (Fig. 1). Irrigation water was collected within the strip

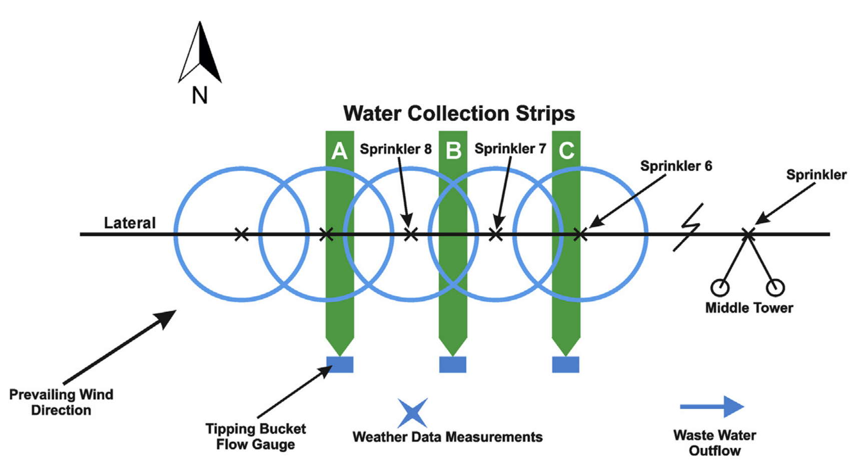

Fig. 2 – Experimental design of the field sampling.

using a large waterproof tarpaulin that was placed over the strips creating impermeable surface to prevent any infiltration during the experiment. The tarpaulin was green in colour to simulate the presence of a very short and uniform plant canopy. Attention was paid not to produce significant wrinkles when installing the tarpaulin. The edges of the tarpaulins at each side of the strips were attached to the ground by being buried in adjacent soil and held down with heavy objects. For additional precaution, 6 rectangular asphalt shingles (1020 mm × 340 mm × 30 mm) were placed inside each strip every 3 m to fix the inside tarpaulin to the ground and prevent the wind from blowing underneath.

Local meteorology was measured 2 m upwind of strip B (Fig. 2) in the prevailing wind direction using a cup anemometer (014 A-L; Campbell Scientific Inc., Logan, UT, USA), a wind direction sensor (024 A-L; Campbell Scientific Inc.) and a temperature-relative humidity probe (T and RH, PC72V; Michell Instruments Ltd., UK), and data were acquired at 1 s execution interval by a datalogger (CR-3000, Campbell Scientific Inc.). All sensors were mounted at 0.75 m a.g.l. height.

At the outlet of each strip (runoff catchment), a pit was dug (0.9 m × 0.7 m × 0.4 m) to install the tipping bucket rain gauges below grade. The tipping buckets were covered by triangular shaped wooden shields to prevent bias due to wind, dust, evaporative demand and/or falling soil (Fig. 1). Their data were acquired at a 0.01 s execution interval by the datalogger. A trench was dug to drain the wastewater produced by these tipping buckets.

A total of 8 controlled irrigation tests were carried out in 2014 as part of this study, (Table 1). Among these, 2 tests were made under windy conditions, and the remaining tests were conducted during calmer winds with high (and sometimes extreme) temperatures (Table 1). An instantaneous flow rate (q) for each of the three strips was estimated by:

$$q = \frac{0.5 \times \alpha}{\Delta t} \quad (1)$$

where 0.5 is the bucket volumetric capacity (0.5 l); α is the calibration coefficient determined for each of the three tipping buckets; and Δt is time difference between two consecutive tips (min). 5-min average values of the WAE (WAE_{5min}) were then calculated by dividing the average flow rate from all 3 strips by the average sprinkler nozzle flow rate ($q_{av} = 13$ l min^{-1}), and correcting by the ratio of strip width (β) to sprinkler head spacing (λ) as follows:

$$WAE_{5min} = \frac{\left(\sum_{j=2}^{n} q_{A,j} + \sum_{j=2}^{m} q_{B,j} + \sum_{j=2}^{p} q_{C,j}\right) \times \lambda}{q_{av}(n+m+p-3)\beta} \quad (2)$$

where, n, m and p are the total number of tips over 5-min for strips A, B and C, respectively; j is an index representing the tip number within each 5-min interval (*i.e.*, $1 \le j \le n$ for strip A, $1 \le j \le m$ for strip B and $1 \le j \le p$ for strip C); $q_{A,j}$, $q_{B,j}$ and $q_{C,j}$ are the flow rates for strips A, B and C, respectively, after the j^{th} tip, which were evaluated using Eq. (1). For example, $q_{B,4}$ refers to the flow rate for strip B after the occurrence of the 4th tip. For each sigma, j starts from 2 since the first flow rate could not be calculated unless the second tip occurred. The value of 3 inserted in the denominator was due to the fact that for each strip and for each timing interval (*i.e.*, 5-min), the total number of calculated flow rates was always equal to the total number of tips for that strip minus 1.

To validate this study, catch cans were also concurrently installed and collected during these events. For this purpose, 108 plastic commercial cans (110 mm diameter, 130 mm height) were installed inside – and outside strips A and B. The spatial design consisted of 6 rows of 18 catch cans each with 1 m spacing. Two rows (out of the 6) were placed in the centreline of the strips. The duration of each test was at least 45-min (Table 1). After the sprinklers were shut off, the catch can collection was estimated in <20-min. Water depth was calculated by dividing the volume collected by the surface area of the aperture of the catch can. Water evaporation from the cans during the experiment was taken into account empirically, by filling a single can with a known volume of water, placing it outside the influence of the irrigation, and measuring it before and after the test (Ortiz et al., 2009; Pláyan et al., 2005). To decrease the collector evaporation losses, the cans were pre-wetted before a test.

WAE from the catch can method was estimated by:

$$WAE_{can} = \frac{\lambda \times 1 \sum_{i=1}^{108} z_i}{L q_{av} t} \quad (3)$$

where λ is sprinkler head spacing (3 m); L is total distance between the first and the last row of cans (6 m); q_{av} is sprinkler discharge (0.013 m^3 min^{-1}); t is irrigation time (min) (Table 1); 1 m^2 is the surface area represented by each catch can; z_i is the catch can irrigation depth after taking evaporation into account (m) and; n-size = 108 total number of catch cans, *i.e.*, i = 1,2, …,108.

Table 1 – Time, duration of each test, and weather conditions.

Test	Date	Test duration (min)	Average temperature (°C)	Average RH (%)	Average wind speed (m/s)	Maximum wind speed (m/s)
1	8 May	90	15.5	71.9	3.9	5.7
2	9 May	90	16.2	43.8	4.8	5.9
3	25 Aug.	60	23.8	54.8	1.1	1.7
4	25 Aug.	90	27.4	42.9	0.9	1.5
5	26 Aug.	90	19.9	63.5	0.6	1.2
6	26 Aug.	45	25.6	44.7	0.9	1.2
7	26 Aug.	90	32.6	24.7	0.9	1.7
8	28 Aug.	90	25.2	46.6	1.5	1.9

Estimates of WAE from the strip and catch can methods had different sampling intervals, *i.e.*, 5-min verses the total period of the test, respectively. Because the aim was to validate the strip results against the catch can method, a global WAE was derived (here called WAE_{Strip}) for the strip test by inserting *n*, *m* and *p* (for strips A, B and C respectively) in Eq. (2) as the total number of tips for each complete test.

2.1. Data analysis (statistics)

Mixed modelling methods with variance–covariance matrices explicitly formulated to appropriately account for the random effects of the experimental design, were used to evaluate drivers of WAE and the differences in WAE_{Strip} and WAE_{Can} (catch can method). Variance–covariance parameters were estimated via restricted maximum likelihood using the SAS procedure PROC MIXED (v.9.4, SAS Institute Inc. Cary, NC, USA). The model included fixed effects for the method (catch can and strip), average wind direction (θ), and average and maximum air temperature (°C), relative humidity, and wind speed (m s^{-1}). Random effects were included for the test number (1–8) and test duration (min).

Mixed modeling methods were used to explore the effects of environmental conditions on the WAE_{5min} with fixed (temperature, wind speed and relative humidity) and random effects (test and time). Explanatory variables were explored strategically due to high correlation among parameters (Table 2) to prevent multi-colinearity. Parameter selection was based on the Wald chi-square statistics, and parameters were removed from the model if they were not influential ($P > 0.05$). Goodness-of-fit statistics, Akaike's information criteria (AIC) and Bayesian information criteria (BIC), were used to compare models. AIC and BIC are model selection statistics appropriate for non-nested models, which measure how close fitted values are to true values, with a penalty for the number of parameters in the model (Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2006). At each step in model selection, the significance of each model parameter was evaluated to ensure that the final model had the lowest AIC and BIC values. To test for differences among levels of categorical variables, least square means were produced, which are the marginal predicted mean values for the model-dependent variable given all other variables in the model are at their average values. Differences among means were tested with the Tukey–Kramer multiple comparisons test. Assumptions of normality and homoscedasticity were evaluated visually by plotting residuals.

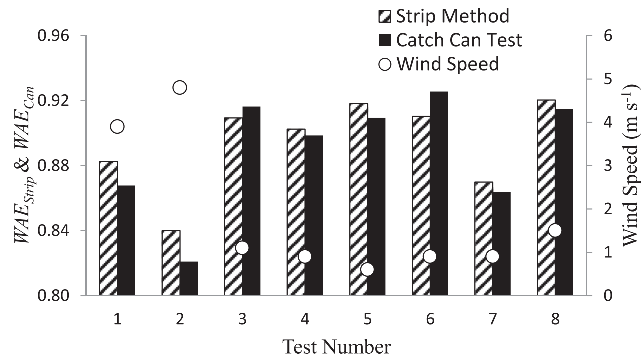

Fig. 3 – WAE_{Strip}, WAE_{Can} and average wind speed.

3. Results and discussion

3.1. Validation with catch can data

Good agreement was observed between the catch can (WAE_{Can}) and the strip (WAE_{Strip}) methods for all tests, with a maximum difference being only 2.3% (Fig. 3). Tests 1 and 2 showed the largest difference between methods, which occurred under high wind speeds (Fig. 3). The mixed effects model supports these observations showing that there was no significant difference between methods ($p = 0.4135$), and that the WAE_{Strip} and WAE_{Can} had both a significant negative relationship with average wind speed ($p = 0.0829$) (Table 3; Fig. 4). The interaction between methods and wind speed, suggests

Table 2 – Pearson's correlation coefficients for explanatory variables and WAE_{Strip} and WAE_{Can}.

r / *p-value*	Wind direction	Air temperature (average)	Air temperature (max)	Relative humidity (average)	Relative humidity (max)	Wind speed (average)	Wind speed (max)
Wind Direction							
Air Temperature (Average)	−0.7178 0.0017						
Air Temperature (Max)	−0.6945 0.0028	0.9936 <0.0001					
Relative Humidity (Average)	0.6989 0.0026	−0.7797 0.0004	−0.7217 <0.0001				
Relative Humidity (Max)	0.7054 0.0023	−0.7996 <0.0001	−0.7338 <0.0001	0.9850 <0.0001			
Wind Speed (Average)	0.3611 0.1695	−0.7473 0.0009	−0.7665 <0.0001	0.2609 0.3291	0.3562 0.1757		
Wind Speed (Max)	0.3500 0.1839	−0.7517 <0.0001	−0.7573 0.0007	0.3232 0.2220	0.4274 0.0987	0.9886 <0.0001	
$WAE_{Strip/Can}$	0.1232 0.6494	0.3147 0.2352	0.3569 0.1748	0.2323 0.3865	0.1382 0.6098	−0.7778 <0.0001	−0.7680 <0.0001

Table 3 – Mixed modeling effects for WAE_{Strip} and WAE_{Can}.

Effect		Estimate	Standard error	Pr > |t|
Intercept		0.9317	0.04176	<0.0001
Method				
WAE_{Can} vs. WAE_{Strip}		0.004248	0.004843	0.4135
Average Wind speed		−0.01373	0.006702	0.0829
Wind speed * Method				
Wind Speed	WAE_{Can} vs. WAE_{Strip}	−0.00592	0.003248	0.0587

that as wind speeds increased, the WAE_{Can} was lower than WAE_{Strip} ($p = 0.0587$; Table 3; Figs. 4 and 5c). However, high correlation between explanatory factors (Table 2) restricted the inclusion of more than one explanatory factor in the final mixed effects model.

Wind speed was highly correlated with mean and maximum air temperature ($p < 0.001$; Table 2). High covariance between wind speed, air temperature, and relative humidity suggests that interacting effects may be important though difficult to quantify due to the sample size, and high spatial and temporal covariance. Linear relationships between the difference between methods, air temperature (Fig. 5a), relative humidity (Fig. 5b), and wind speed (Fig. 5c) were also observed and this suggested that WAE_{Strip} was enhanced by lower temperatures (<24 °C) and appeared to be less sensitive to higher wind speeds (>1.69 m s^{-1}; Fig. 5). The WAE_{Can} was higher when temperatures were ~24 °C and at lower wind speeds (<1.69 m s^{-1}; Fig. 5).

3.2. *Sources of errors*

It was assumed that random effects were the same for both approaches. It was also assumed that systematic sources were the same for both measurement systems, but the effects of these sources differed. For example, i) ***collection efficiency***: there is a variance in the sprinkler's ability to distribute water spatially, which was assumed to be better captured by the larger strips compared to the smaller surface area. Hendawi et al. (2005) reported that catch can collection efficiency is generally reduced under high wind conditions and becomes further reduced when droplet sizes are very small (*i.e.*, < 0.5 mm). In our study, however, most of the droplet sizes were between 1 and 2 mm (King, private communication) thus the catch can efficiency should be >95% (Hendawi et al., 2005). Here, the collection efficiency of both systems was assumed to be 100%, because the sources of error differ in part, *i.e.*, water collected by strips is continuous verses discrete collection by the catch cans. However, under high wind conditions, the WAE_{Can} was lower than WAE_{Strip} (Figs. 3 and 4). Thus, if the collection efficiency of cans is fully accounted for, our estimate of 2.3% error reported may be reduced, ii) ***evaporative losses and surface capacitance***: the amount of surface area and surface capacitance differ between the two methods. This exposes the strip method to potentially large evaporative losses. To account for this potential bias, wind speed and temperatures (*i.e.*, water temperature under the irrigation source which is close to the wet bulb temperature Sadeghi, Peters, Cobos, Loescher, and Campbell (2013), and tarpaulin temperatures that change with incident solar radiation, air and water temperatures) should be measured directly. The WAE results were re-evaluated by neglecting the water

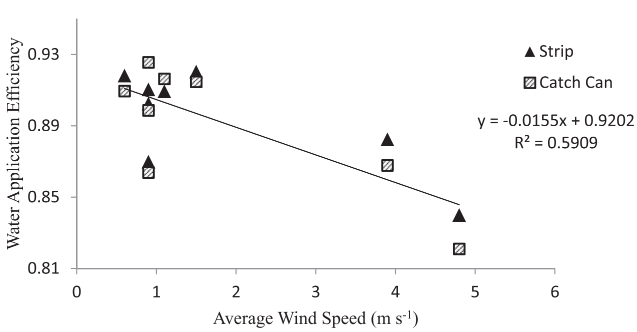

Fig. 4 – Linear relationships between wind speed (m s^{-1}) and WAE_{Strip} and WAE_{Can} (P < 0.001).

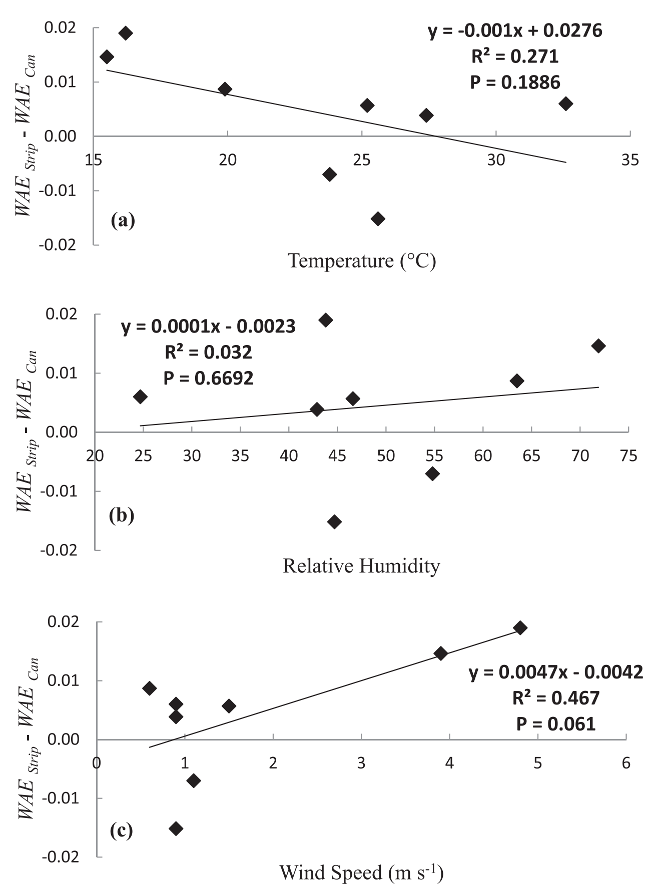

Fig. 5 – Linear relationship between the residuals from WAE_{Strip} – WAE_{Can} and (a) air temperature, (b) relative humidity, and (c) wind speed.

evaporation from the cans during the experiments. It was concluded that there was a relative difference of only 0.1% in the final (total) WAE output by the catch can method. Therefore, this affect was discounted in the interpretation as other researchers have done (e.g. King et al., 2012; Ortiz et al., 2009; Plyán et al., 2005). Empirically assessing this source of bias was not within the scope of this study, and it was assumed to be lower in magnitude than the bias due to the (in)ability to assess the changing environmental conditions that control WAE, and i.e., temporal averaging—which is within the scope of this study, and iii) ***Hysteresis effect***: It is acknowledged that evaporative losses change exponentially throughout the day due to changing environmental conditions, e.g., increases in air temperature (Campbell & Norman, 1998). Although the strips exposed more surface area than the cans, both were subject to the same diurnal hysteresis in evaporative demand. It can be assumed that the overall evaporative quantities are orders of magnitude smaller than the gross collection amounts that we wish to compare, and to discount this effect. In addition, the water captured water by the strips was in the form of droplets which quickly reached the main stream that was flowing towards the outlet. Therefore, the effect of hysteresis on the measured WAE was likely to be minimal.

3.3. *Comparison with other methods*

As an alternative method for measuring WAE over short timing intervals a network of tipping bucket rain gauges (TBRG) could be used. The TBRG method has several shortcomings, such as; i) the need to have numerous (and costly) collectors with the same collection area as the strip method, and to account for a spatial representative mean and variance (Loescher et al. 2002), ii) higher maintenance efforts/cost, iii) additional source of error in breakthrough volume and over spill in the tipping mechanism (a the common problem of the tipping mechanism is not operating sufficiently rapidly to cope with quantity of water delivered to the collector), and iv) the spatial averages would be compromised if one (or perhaps several) tipping buckets were damaged during the experiment. Interpolation would be a good solution to fill the gap in spatial coverage, but it would also introduce another source of uncertainty. This source of uncertainty would be further compounded if wind speed and direction changed during the test (rf. Dechmi, Playán, Cavero, Faci, & Martínez-Cob, 2003). The strip method on the other hand, does not embody any of these operational shortcomings or uncertainties.

3.4. *Measuring* WAE_{5min}

WAE_{5min} was variable and changed even over a 45-min test (e.g test 6 in Fig. 6). In tests with very high wind speeds, WAE_{5min} varied from 80 % to 92 % and from 77 % to 95 % (Fig. 6). The WAE_{Can} for the two tests returned average values of 87% and 82%, respectively. Variations in WAE_{5min} persisted at lower values under low wind conditions (tests 3–8). This can be attributed to the abrupt changes of wind direction during the experiments, (see Fig. 4). All these observations confirm again that the catch can method failed to capture the dynamic variation of the WAE with time.

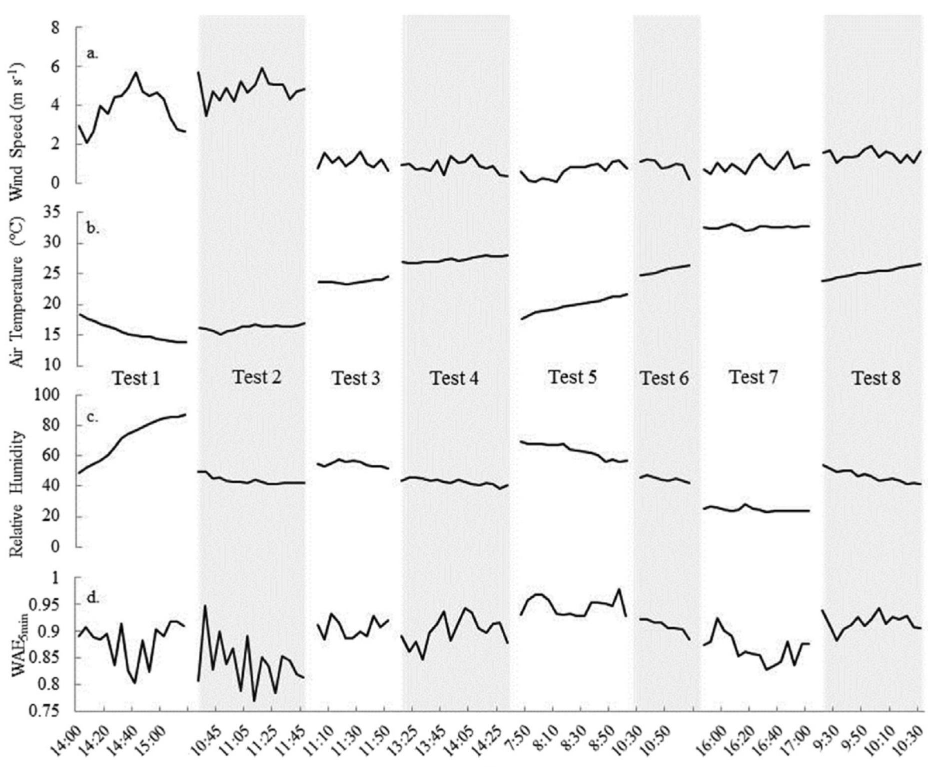

Fig. 6 – Time series of (a) wind speed, (b) air temperature, (c) relative humidity, and (d) the WAE_{5min} for each test.

Table 4 – Mixed modeling effects for WAE_{5min}.

Effect	Estimate	Standard error	DF	t Value	Pr > |t|
Intercept	1.0518	0.02733	9.17	38.48	<0.0001
Temperature	−0.00462	0.00097	7.87	−4.77	0.0015
Wind Speed	−0.0264	0.00331	13.3	−7.97	<0.0001

3.5. *Drivers of the* WAE

In a similar manner to the effects of environment on WAE_{Can} and WAE_{Strip}, WAE_{5min} decreased with both temperature and wind speed and increased with relative humidity. However, only the correlations with temperature ($p = 0.002$) and wind speed ($p < 0.001$) were significant, not for relative humidity (Table 4). When considering the WAE_{Strip} and WAE_{can}, only wind speed showed a significant relationship (Table 2). This indicates that evaluating the WAE over short time intervals (e.g. 5 min) may be a better way to study its drivers even though the instantaneous effects of the weather variables on WAE_{5min} cannot be established due to the inherent time lag in the measurements.

Although the relationship between relative humidity and WAE was not significant, neither for WAE_{5min} nor for WAE_{Strip}, it is likely that this parameter is also important driver of WAE, as has been shown for WDELs using center pivots (Harrison, 1993; McLean et al., 2000; Ortiz et al., 2009; Playán et al., 2005). This further suggests that all the drivers of evapotranspiration (ET) also control WAE, i.e., Penman Montieth, or Priestly & Taylor equations (Allen, Pereira, Raes, & Smith, 1998; Keller & Bliesner, 1990; Monteith & Unsworth, 1990; Priestly & Taylor, 1972; Steiner, Kanemasu, & Clark, 1983). The question is, under what conditions do specific parameters exert the most control. For example, Clark and Finley (1975) found winds > 4.5 m s^{-1} controlled evaporative losses (i.e. aerodynamic conductance terms became important, Steiner et al. 1983), and at lower windspeeds, vapour pressure deficit exerted a greater control. A similar conclusion can be drawn from Playán et al. (2005) who found that wind speed best explained WAE when data from both day and night measurements were grouped together, but not when night time data was used alone, suggesting that aerodynamic conductance with a lack of (night time) evaporative demand does not control ET. While biophysical models can provide insight on the abiotic drivers of WAE, irrigation is inherently applied to the agronomic system, thus imposing interactive effects of the abiotic drivers and the physical structure of the irrigation system. For example, Playán et al. (2005) suggested that sprinkler height above the surface roughness should be taken into account given the vertical wind profiles, and Steiner et al. (1983) found that orientation of the irrigation system to mean wind direction can also affect WAE. Not only are the designs of sprinklers becoming important, but also how they are situated in the agronomic system, i.e. height within the surface layer distance from roughness elements (Monteith & Unsworth, 1990). Taken in concert, our study also suggests that the integration of biophysical approaches (e.g. Penman-Montieth controls on ET), hydrological approaches to the estimate of WAE, runoff, and capacitance (e.g. a Rutter-type model, Calder, Wright, & Murdiyaso, 1986; Loescher, Gholz, Jacobs, & Oberbauer, 2005; Loescher et al. 2002) along with design attributes of the irrigation system and where it is located above the plant canopy, will advance our understanding of WAE and help better optimise irrigation efficiencies as a whole.

4. Conclusions

A strip method of water distribution measurement was proposed for the measurement of wind drift and evaporation losses under linear moving or center pivot sprinkler irrigation systems and this was validated against the standard catch can technique. Compared to the catch can method, this new approach has the advantage of measuring WDELs continuously and provides more information on how changing weather and environmental conditions affect WAE Our results indicated that the instantaneous WAE (here measured every 5 min) is dynamic in time and space, and can make site- and system-specific characterisation more pertinent. In general, it was concluded that the difference between the maximum and the minimum WAE_{5min} is high when wind speeds are high. The strip technique should assist in developing a predictive capacity (for the WAE) and meet the increasing need for enhancing the efficiency of delivering irrigation water. The technique could provide the context for future investigations to more accurately estimate the continuous variation of wind drift and evaporation losses over short time intervals, for long time periods, and when canopy is present or not.

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