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Effects of agricultural management on measurements, prediction, and partitioning of evapotranspiration in irrigated grasslands

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ABSTRACT

Irrigation is an important component of the hydrologic cycle in agricultural ecosystems, affecting both quantity and quality of surface and ground water. Well-managed irrigation involves balancing irrigation with water consumption by evaporation and transpiration (collectively evapotranspiration), maximizing ecosystem water-use efficiency and minimizing drainage. Here we compare rates of actual crop evapotranspiration (ET_C) measured by eddy covariance with reference evapotranspiration (ET_0) calculated from meteorological variables for two irrigated ryegrass systems in central South Island, New Zealand between June 2011 and March 2013. The sites were similar in climate, but contrasted in management: one grazed by dairy cattle and the other harvested annually for seed. Over the first year of measurements, cumulative ET_C was very similar at the two sites, totalling 791 and 819 mm for the dairy pasture and seed crop respectively, although temporal patterns of partitioning of ET_C amongst evaporation and transpiration differed as a result of management activities. Responses of ET_C to global radiation, temperature and vapour pressure deficit were all similar during active growing season periods. Differences between the two sites were observed at the end of the second measurement season, when irrigation was ceased in the seed crop prior to final harvest and ET_C was reduced compared to ET_0. As a result, cumulative ET_C was 13% greater for the dairy pasture at the end of the study period.

1. Introduction

Evapotranspiration is an important component of ecosystem water balance, typically equalling 50% or more of precipitation (Williams et al., 2012). Efficient agricultural water management depends upon the precise balance of irrigation and precipitation with water consumption by actual crop evapotranspiration, ET_C. The consequences of unbalanced irrigation practices include plant water deficits, which reduce crop yields (Zwart and Bastiaanssen, 2004), and excessive soil drainage, which may increase nutrient leaching rates (Martin et al., 1994). Thus, a good understanding of controls on evapotranspiration is required for efficient management of water resources.

Available energy from net radiation and atmospheric demand for water vapour are the primary drivers of ET_C. Numerous models, which range in complexity, have been developed for predicting potential rates of evapotranspiration from meteorological data (Allen et al., 1998; Penman, 1948; Priestley and Taylor, 1972). However, these models are typically underpinned by the assumption of a well-watered reference crop and require correction in order to properly represent ET_C (Sumner and Jacobs, 2005). In particular, vegetation can be an important source of variation in rates of ET_C. Vegetation can influence ET_C through its effect on physical properties, such as available energy and albedo (Wang et al., 2012), surface properties, such as surface roughness (Monteith and Unsworth, 2013), and through direct stomatal control of transpiration (Jarvis and McNaughton, 1986).

In agricultural landscapes, management practices influence species composition, leaf area, plant nutrition and phenology, all of which may impact ET_C. Grazing of grasslands is a particularly widespread management practice, extending to 25% of the global land area (Asner et al., 2004). Grazing can lead to reduction in ET_C relative to ungrazed sites (Bremer et al., 2001; Frank, 2003; Miao et al., 2009; Wang et al., 2012), impacting catchment-scale water

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balance (Fatichi et al., 2014). However, this effect is not universal (Pronger et al., 2016; Rosset et al., 2001; Stewart and Verma, 1992) and changes in ET_C are difficult to link directly to grazing-induced changes in leaf area.

Within New Zealand, grazing systems are an important land use, with 5.7 Mha (21% of land area) of high-producing grassland used primarily for grazing and silage production (Ministry of Environment, 2015). Increasingly, agricultural production has shifted from low-intensity, dryland farming to high-intensity grazing for dairy. The number of dairy cattle within New Zealand increased by 27% over the period 2005–2012 (Statistics New Zealand, 2013). Correspondingly, irrigated land area has increased by 17% over the same period to support additional productivity. The majority of this increase has occurred in the Canterbury region.

The objective of the current study is to determine the impact of two management practices common within the Canterbury region on measurement of ET_C in irrigated grasslands. We compare seasonal patterns and accumulation of ET_C and predictions of potential evapotranspiration from a dairy pasture subjected to rotational grazing with a ryegrass crop harvested annually for seed over the period June 2011 to March 2013. The response of ET_C to environmental drivers and variations in leaf area is also investigated. These measurements are essential for integrating management practices into predictions of ET_C and development of best-practice techniques for managing irrigation in response to daily and seasonal demand from ET_C. These data could also provide the basis for optimizing land-use within water-limited irrigation schemes.

2. Materials and methods

2.1. Site description

Study sites selected for comparison were a dairy farm and crop farm located in the Canterbury Plains region, South Island, New Zealand. Both sites are on alluvial soils under similar climatic conditions. The dairy pasture site (43°40′26.61″S, 171°35′27.63″E, elevation: 309 m) was a high-producing, rotationally grazed mix of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). Soils at the site are Lismore pallic firm brown (Typic Dystrustept) (Hewitt, 2010; Soil Survey Staff, 2006) with a field capacity of 0.28 $m^3\ m^{-3}$ and wilting point of 0.10 $m^3\ m^{-3}$ for the top 300 mm of soil (Landcare Research, 2016). The crop farm (43°58′14.25″S, 171°47′41.78″, elevation: 47 m) was planted in perennial ryegrass which was mowed to a height of approximately 150 mm each year in October and allowed to grow until February when it was harvested for seed. The site was also grazed by sheep or mowed periodically over the winter (May through September). Following the second harvest in February 2013, the site was sprayed with herbicide in preparation for a new crop. Soils at the site are Templeton typic immature pallic (Udic Haplustept) (Hewitt, 2010; Soil Survey Staff, 2006) with a field capacity of 0.34 $m^3\ m^{-3}$ and wilting point of 0.17 $m^3\ m^{-3}$ (Landcare Research, 2016).

Over the measurement period, 11 June, 2011–4 March 2013, mean daily air temperature was 8.6 and 9.1 °C for the pasture and crop sites, respectively. Mean incoming solar irradiance was 166 $W\ m^{-2}$ for the pasture and 168 $W\ m^{-2}$ for the crop site. The pasture site received approximately 30% more rainfall (Table 1), which is consistent with an East-West gradient in precipitation across the Canterbury region along which the sites are situated (Srinivasan and Duncan, 2011; Tait et al., 2006). Both sites were irrigated throughout the summer months (October through April) in order to minimize soil water deficits (Fig. 1, Table 1). Irrigation amounts were similar, however the application method differed between the sites. A linear irrigator applied up to 60 mm d^{-1} of irrigation 3–5 times during the irrigation season for the seed crop. A central pivot irrigator was used in the dairy pasture, applying water at lower rates (<15 mm d^{-1}) more frequently (4–5 day return interval).

2.2. Micrometeorological measurements

The eddy covariance method was used to measure sensible (H) and latent heat (LE, energy equivalent of evapotranspiration) fluxes, as well as fluxes of CO_2 (Baldocchi et al., 1988). Each site was equipped with a sonic anemometer (CSAT-3, Campbell Scientific, Logan, UT USA) and open-path CO_2/H_2O analyser (LI-7500A, LI-COR, Lincoln, NE USA) mounted at 2.3 m height. Ancillary meteorological measurements included net radiation (CNR2, Kipp and Zonen, Delft, Netherlands), global radiation (LI-200, LI-COR, Lincoln, NE USA) and soil heat flux (HFP01SC, Hukseflux, Delft, Netherlands). Soil temperature (TCAV, Campbell Scientific, Logan, UT, USA) and volumetric water content (CS615, Campbell Scientific, Logan, UT USA) were measured at 100 mm soil depth. Precipitation and irrigation were measured by tipping bucket rain gauges located within and immediately outside the irrigator footprint.

Raw, 10 Hz 3-dimensional wind speed and CO_2/H_2O concentrations were processed to 30 min average fluxes using EddyPro processing software (v 5.2.1, LI-COR, Lincoln, NE USA). Corrections were applied for density fluctuations (Webb et al., 1980), high-frequency spectral losses (Moncrieff et al., 1997), sonic temperature (Schotanus et al., 1983), and anemometer misalignment (Wilczak et al., 2001) within the EddyPro software package.

Resultant 30-min fluxes were screened for physically unrealistic values ($LE < -200\ W\ m^{-2}$, $LE > 800\ W\ m^{-2}$, $H < -500\ W\ m^{-2}$, $H > 1000\ W\ m^{-2}$, CO_2 flux > 40 $\mu mol\ m^{-2}\ s^{-1}$, CO_2 flux < −40 $\mu mol\ m^{-2}\ s^{-1}$). Fluxes with poor signal quality from the infrared gas analyser (AGC > 50), typically caused by irrigation, rain or dew on the sensors, were removed. Quality tests for stationarity and turbulent development were also used as filter criteria (Mauder and Foken, 2004). Further outliers in the 30 min flux record were removed according to Papale et al. (2006), using a conservative spike threshold (z) of 5.5. Turbulence measurements from wind directions between 190° and 280° at the pasture site and between 165° and 250° at the crop site were compromised due to interference from the tower structure and sensor arrangement and were removed. Overall system performance was assessed by comparing turbulent energy fluxes ($LE + H$) with available energy measured by net radiometer. Half-hourly energy budget closure was 78 and 77% percent for the pasture and crop sites respectively (as estimated from the slope of linear regression), very similar to the 80% average closure reported for FLUXNET sites (Wilson et al., 2002).

Gaps in the LE, H and CO_2 flux time series due to either missing or poor quality data were filled following Falge et al. (2001). Briefly, missing values were filled from a look up table of mea-

Table 1

Total precipitation (P, mm), irrigation (I, mm), actual evapotranspiration (ET_C, mm), FAO-56 reference evapotranspiration (ET_0, mm) estimated from Eq. (1), soil evaporation (E_S, mm) estimated from Eq. (2) and gross primary production (GPP, $g\ C\ m^{-2}\ d^{-1}$) for the two measurement years (11 June2011–10 June 2012 and 11 June 2012–4 March 2013) at the dairy pasture and ryegrass seed crop sites.

	Year 1		Year 2[a]	
	Pasture	Crop	Pasture	Crop
P	843	604	666	527
I	173	218	137	128
ET_C	791	829	819	598
ET_0	945	929	805	739
E_S	252	153	225	166
GPP	2827	2628	2155	2009

[a] Incomplete year.