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Low spatial and inter-annual variability of evaporation from a year-round intensively grazed temperate pasture system

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ABSTRACT

Ecosystem scale measurements of evaporation (*E*) from intensively managed pasture systems are important for informing water resource decision making and validation of hydrologic models and remote sensing methods. We measured *E* from a year round intensively grazed temperate pasture system in New Zealand using the eddy covariance method for three years (2012–2014). Evaporation varied by less than 3% both spatially (770–783 mm) and temporally (759–776 mm) at an annual scale. The low spatial and temporal variation largely occurred because *E* was strongly controlled by net radiation ($r^2 = 0.81$, $p < 0.01$, daytime, half-hourly), which did not vary much between sites and years. However, *E* was strongly limited when volumetric moisture content (VMC) declined below permanent wilting point causing a strong reduction in the decoupling coefficient and an increase in the Bowen ratio. Grazing events appeared to have no effect on *E* during autumn and winter but reduced *E* by up to 5% during summer and spring while complete removal of vegetation during autumn herbicide application reduced *E* by ~30%. This implied that over the pasture regrowth period soil water evaporation (E_S) could provide up to 70% of *E* relative to a vegetated site (during autumn) and, given that grazing events removed about 60% of leaf area, these findings suggest E_S was likely able to compensate for decreased transpiration post-grazing. Agreement between measured *E* (E_{EC}) and FAO-56 reference crop *E* (E_o) was good when soil moisture limitation was not occurring. However, during periods of soil moisture limitation E_o exceeded E_{EC} and a correction factor was needed. We trialled the water stress coefficient (K_s) and a simple three bin VMC correction factor (K_{VMC}) and found the K_{VMC} approach worked better at a daily and monthly scale while both approaches worked well at an annual scale.

1. Introduction

Grazed pastures cover about 26% of the global ice free land area (Steinfeld et al., 2006) occupying a larger area than any other land use (Asner et al., 2004). In many parts of the world more intensive rotational grazing of these systems is occurring to increase global food production largely supported by increased fertiliser use (Tilman et al., 2002; Woodford, 2006). A major constraint to pasture production is the availability of water and this availability is largely controlled by the balance between precipitation and evaporation (*E*). Measuring *E* is difficult and expensive and therefore published measurements of *E* from pastoral systems are scarce. Evaporation measurements are fundamental for understanding hydrological processes, land-atmosphere interactions and terrestrial ecosystem function (Kelliher et al., 1993) and the relative scarcity of measurements is a limitation to the development and validation of Earth system models, primary production models, and remote sensing methods for grassland systems (Seaquist et al., 2003).

Grasslands are generally poorly coupled to the atmosphere (McNaughton and Jarvis, 1991) and therefore the dominant controls on evaporation are typically available energy and water (e.g. Brummer et al., 2012). Available energy and water are highly variable between grassland sites because of differences in climate resulting in large variation in evaporation patterns and annual totals (Krishnan et al., 2012). Globally, there is a strong correlation between total annual precipitation and evaporation (Zhang et al., 1999, 2001) demonstrating that variation in annual precipitation patterns and totals will drive variation in *E* among grasslands. Other factors including turbulent transport (or aerodynamic conductance) and vegetation diversity, density, and structure can also cause variation in *E* among grasslands (Frank, 2003). Ultimately, evaporation from grasslands is controlled by a combination of meteorological factors (net radiation, air

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temperature, humidity, and wind speed), crop characteristics (stomatal control, plant height, rooting depth, leaf area, roughness and albedo), and land management and other environmental factors (soil moisture content, soil physical structure, nutrient availability) (Allen et al., 1998).

Intensive rotational grazing of pasture systems causes regular and rapid reductions in leaf area and this biomass removal, followed by regrowth, could affect *E*. Evaporative water loss occurs via three pathways including direct evaporation of soil water (E_S), intercepted liquid water from plant surfaces (E_I), and through the plant system via transpiration (E_T). The partitioning among these three pathways is largely dependent on leaf area (Kelliher et al., 1995; Allen et al., 1998). A reduction in leaf area usually reduces E_T and E_I but can lead to increased E_S (soil compensation) because more radiation and rainfall will reach bare soil surfaces (Bremer et al., 2001; Frank, 2003; Wang et al., 2012). Reduction in leaf area through grazing has, in some cases, been shown to reduce total *E* by up to 40% on daily time scale (Bremer et al., 2001), and 6–7% on annual time scale (e.g. Day and Detling, 1994; Bremer et al., 2001; Frank, 2003) while in other circumstances grazing appears to have had no effect (Shuttleworth et al., 1989; Stewart and Verma, 1992; Wang et al., 2012). Currently, we do not know whether grazing reduces total *E* largely because of uncertainty around the degree to which increases in E_S compensate for reductions in E_T (see Falge et al., 2005).

Models are often used to predict *E* because of the difficulty and expense involved in direct measurement (Green et al., 1984; Fisher et al., 2005). A number of models have been developed for this purpose including by Penman (1948), Penman-Monteith (Monteith, 1965), Priestley and Taylor (1972), McNaughton and Black (1973), and Shuttleworth and Wallace (1985). In the past, Priestley and Taylor (1972) has often been used and recommended in pasture systems (e.g. Green et al., 1984) largely because it required minimal input data (net radiation and temperature). However, more recently Allen et al. (1998) have parameterised the Penman-Monteith model and the Food and Agriculture Organisation of the United Nations (FAO) now recommend this parameterised version (FAO-56) as the standard method for estimating *E* for crops and pasture. The development of this equation was considered a significant milestone in enabling a consistent *E* estimation methodology (Howell and Evett, 2004). FAO-56 has since been widely used to estimate *E* (Steduto et al., 2003) in larger and more complex water balance, ecosystem, and Earth system models and is therefore important for the evaluation of water resources, management and monitoring crop water requirements, drought forecasting, and the study of climate change (Zhao et al., 2013). Despite the recognised importance and wide-spread use of the FAO-56 version of Penman-Monteith there have been few comparisons between the model and field scale measurements for intensively grazed temperate pastures.

In their 1993 review, Kelliher et al. (1993) highlighted the need for more ecosystem scale measurements of *E* from grassland systems, and surprisingly, more than 20 years later there is still a paucity of data from intensively grazed pasture systems. For example, a recent modelling study by Ma et al. (2015) included measurements of *E* from multiple grazed pasture systems across Europe. While some of the sites were identified as intensively grazed the mean stocking rate was 0.68 dairy cows ha^{-1} which is low compared to intensively grazed systems in New Zealand which often exceed 3 dairy cows ha^{-1}. Other grassland *E* research has largely focused on un-grazed systems (e.g. Wever et al., 2002; Burba and Verma, 2005; Hao et al., 2007; Kurc and Small, 2007; Chen et al., 2009) or very lightly grazed, low productivity systems without year round-grazing (e.g. Hunt et al., 2002; Baldocchi et al., 2004; Li et al., 2006, 2007; Aires et al., 2008; Ryu et al., 2008; Bowling et al., 2010; Krishnan et al., 2012). Furthermore, most *E* studies have been conducted in low rainfall climates, for example, in a summary of *E* studies using the water balance approach (Zhang et al., 1999) over 80% of sites experienced annual rainfall of less than 1000 mm and none were from year-round rotationally grazed systems.

New Zealand farming systems provide an excellent opportunity to measure *E* from high intensity grazing operations that are likely to increase globally as other countries in the temperate zone increase production (e.g. South America). In New Zealand, high producing exotic grasslands cover ~22% of the land surface (5.8 million ha) and about 90% of this area is not irrigated (Ministry for the Environment, 2009) and therefore reliant on rainfall for growth (Moot et al., 2009). Traditionally, New Zealand pasture systems have been dominated by perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) with the temperate maritime climate generally being well suited to dryland ryegrass pastures. These high producing ryegrass and clover pastures typically grow between 14,000 kg and 18,000 kg of dry matter (DM) ha^{-1} year^{-1} (Tozer et al., 2013). Farms are usually subdivided into paddocks of area 2–3 ha and are rotationally grazed year-round with large herds of cows (~200) grazing for short periods of time (often 12–24 h) resulting in sudden and large reductions in pasture biomass and leaf area.

The primary objective of this study was to quantify the magnitude and temporal and spatial variability in *E* from an intensively grazed ryegrass and clover pasture system. A secondary objective was to investigate the relationships between *E* and grazing events to determine whether modelling approaches need to account for grazing to predict *E* from pastoral systems. Finally, measured *E* was compared to modeled *E* using the FAO-56 method. We used three eddy covariance (EC) systems installed on one farm to measure spatial variability and measurements were extended over three years at one site to determine inter-annual variability.

2. Methods

2.1. Site description

The research site was located on a commercial dairy farm in the Waikato region of New Zealand. The climate is temperate with a strong oceanic influence which moderates extremes; however, extended dry periods often occur in late summer and early autumn (Moot et al., 2009). The 30 year (1981–2010) mean annual rainfall and temperature were 1249 mm and 13.3 °C at the nearest climate station 13 km SW of the study sites (NIWA, 2010). The farm was ~207 ha with paddock sizes generally between 2 and 3 ha and grazed by two herds of dairy cows at a stocking rate of ~3.3 lactating dairy cattle ha^{-1}. Pasture species were dominated by perennial ryegrass and white clover. Paddocks were grazed 11–12 times per year. Grazing rotations varied from about 21 days in spring when growth rates reached 70 kg dry matter (DM) ha^{-1} day^{-1} up to 90 days in mid-winter when growth rates declined to about 15–20 kg DM ha^{-1} day^{-1}.

The study area was located within a relatively flat alluvial landscape with gently undulating ridges and swales—remnants of ancestral river channels and levees (McLeod, 1992). Since the river abandoned this path and alluvial deposition ceased some 20,000 years BP (before present) the land surface has been covered by a thin mantle of mainly rhyolitic volcanic ashes up to 0.50 m thick. Variation in sedimentation and drainage on the alluvial surface has resulted in the formation of a complex of four different soil types including the Waihou and Piarere (Typic Orthic Allophanic Soils, Hewitt, 1998), the Te Puninga (Mottled Orthic Allophanic Soil, Hewitt, 1998), and the Waitoa (Typic Orthic Gley Soil, Hewitt, 1998). The Te Puninga soil was dominant and had no significant barriers to roots and high profile available water content (243 mm)