Precision irrigation: trials to assess impacts on crop yield

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Abstract
Trials have been conducted on commercial farms to investigate the impacts on crop yield when irrigation applied from sprinkler irrigation systems is varied to different soil zones according to differences in their moisture status, with the aim of saving water. Soil variability was initially quantified by electromagnetic survey, ground-truthing and laboratory analyses of soil water-holding properties; and management zones were delineated for the irrigation prescription maps. Replicated plots within each soil management zone received one of two treatments: uniform rate irrigation (URI) or variable rate irrigation (VRI). The yield impacts of VRI were neutral, and water savings were between 27 – 55 mm when irrigation was reduced to soils with adequate plant available water and excluded from wet, poorly draining soil zones.

Keywords
Variable rate, yield impact.

Introduction
An unprecedented demand on global freshwater supplies by agriculture is seen as the main cause of increasing global freshwater scarcity (FAO 2011). Land-use intensification and complementary developments such as plant breeding have maintained global food production for a growing global population since the 1960s. However, land-use intensification has increasingly relied on irrigation, and 70% of global freshwater extractions are now used for irrigation purposes. In New Zealand, irrigation demands are closer to 80% of consumptive allocated freshwaters (Aqualinc Research Ltd 2010) and in Australia, irrigation accounts for 50% of total water consumed (ABS 2017). Irrigation systems with improved water-use efficiency (in terms of greater water productivity and reduced drainage) would therefore have a favourable impact on both local and global water scarcity (Hedley and Yule 2009; McCarthy et al. 2014).

Soilscapes and their ability to store and provide water to crops are often variable at sub-field scales, so that ideally irrigation should be varied to improve management of these soil differences. Precision irrigation sprinkler systems with variable-rate technology enable individual nozzle control and can vary irrigation at high resolution (< 10 m) within the operational constraints of individual systems. Our research aims are to develop practical methods to map and monitor soil water status using (i) electromagnetic soil surveys supported by field investigation of the soil profile, and (ii) web-enabled real-time soil moisture monitoring to update prescription maps for a precision irrigation sprinkler system. This provides information so that irrigation can be reduced to specified soil zones where there is adequate plant available water, whilst irrigating other soil zones where plants require water. The goal is to save water without negative impact on crop yield. The aim of this paper is to report results from trials where these VRI strategies were implemented.

Methods
Field sites
Trial sites were established at three farms where existing sprinkler irrigation systems have been retrofitted with new variable rate technology. The three sites are:

- Site 1: 650 m VRI centre pivot irrigating 75 ha of mixed cropping, near Bulls, Manawatu, New Zealand, with maize and wheat grown under the irrigator
- Site 2: 340 m lateral-move VRI system irrigating 111 ha of mixed cropping, near Ashburton, Canterbury, New Zealand, with mixed cropping including beans, wheat, pak choi, and either buckwheat or corn salad crops irrigated simultaneously under one VRI system
- Site 3: 750 m VRI pivot irrigating 170 ha of dairy pasture, Fairlie, South Canterbury, New Zealand.

Derivation of irrigation prescription maps
A map of soil management zones was derived for the area under each irrigation system using electromagnetic mapping with ground-truthing and soil sampling to classify the soil's available water-holding capacity (Hedley and Yule 2009). These digital maps were then loaded into the VRI software control to prescribe varying amounts of irrigation to the VRI trials.

VRI trials
VRI trials were established by marking out replicated plots for two treatments in each soil management zone (Fig. 1). The two treatments were uniform rate irrigation (URI) and variable rate irrigation (VRI). URI applies a uniform amount of irrigation to all plots when the most drought-prone zone requires irrigation. The VRI treatment uses the zone-specific refill point to trigger irrigation events for that zone. The zone-specific refill point is defined as the volumetric soil water content, determined in the laboratory at 100 kPa, and monitored in the field in near real time using wireless sensor networks of capacitance (frequency domain) soil moisture sensors that recorded and uploaded measurements every 15 minutes (Hedley and Yule 2009; Hedley et al. 2013) at Sites 1 and 2. At Site 3, Aquaflex strips (time domain) were installed into the ground (at two depths) to monitor soil moisture in each zone, and the data relayed to the farm office and remote devices in near real-time. The zone-specific refill point can also be estimated as a 'depletion factor' of field capacity (upper drained limit) estimated by real-time soil moisture monitoring.

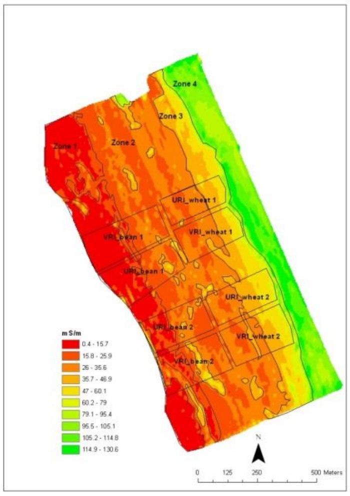

Figure 1. The layout of arable trial plots in four soil management zones at Site 2 to investigate the impact of variable rate irrigation on the yield of a faba bean and wheat crop (Hedley et al. 2013). URI: uniform rate irrigation; VRI: variable rate irrigation.

Yield assessments
At Site 1, replicated square metre plots (n = 4) were hand harvested to assess wheat yield. The whole plants were cut at ground level, oven dried to constant weight at 70°C, and then the grain was removed by threshing in a plot harvester. The grain loss through the thresher is up to 20%. At Site 2 the crops (wheat, faba beans) were harvested with the plot harvester from replicated 10 × 2 m sample areas (n = 2 for wheat; n = 3 for beans) in each trial plot. At Site 3, weekly pasture growth measurements were made using a C-Dax pasture meter in replicated plots. The C-Dax sensor was pulled behind a farm-bike, measuring height of the pasture sward, and this measurement was converted to kg dry matter/ha using a calibration equation. This method was used to assess overall pasture production for each trial plot during the irrigation season.

Results
There was a two- to three-fold difference in total available water-holding capacity at each of the three sites (Table 1) justifying the decision to use VRI systems.

In the URI treatments all plots received irrigation at the same time as the most drought-prone soil zone. The VRI treatment delayed and/or reduced the amount and intensity of irrigation applied to plots in soil zones with poor drainage or adequate plant available water compared with the most drought-prone zones. Overall water savings at the three sites were between 8 and 36%, with less drainage under VRI than URI treatments.

Reduced drainage (during the period of irrigation) was noted by (i) observing the number of drainage spikes in charts provided on a website from near real-time soil moisture monitoring, and (ii) simulated by soil water balance modelling (results not shown). The soils with larger total available water-holding capacity typically receive less irrigation overall, because irrigation is delayed to them at the beginning of the season and then again after major rain events during the irrigation season.

Table 1. Soil characteristics under the three VRI irrigation systems.

Site	Size (ha)	Soil description	Soil apparent electrical conductivity (mS/m)	Available water-holding capacity (mm/root zone)
Site 1: 650m VRI pivot, mixed cropping				
Zone 1	29	Excessively drained, sand	2–5	73 mm/m
Zone 2	36	Well drained, sand	5–8	87 mm/m
Zone 3	6	Imperfectly drained, loamy sand	8–11	160 mm/m
Site 2: 340 m VRI lateral, mixed cropping				
Zone 1	23	Well drained, very stony sandy loam	1–13	67 mm/m
Zone 2	50	Well drained, stony sandy loam	13–53	85 mm/m
Zone 3	22	Mixed sandy loam / silt loam	53–79	115 mm/m
Zone 4	17	Imperfectly drained silt loam	79–132	163 mm/m
Site 3: 750 m VRI pivot, dairy pasture				
Zone 1	33	Well drained, very stony, shallow	4–13	39 mm/60cm
Zone 2	82	Well drained, stony, shallow	13–28	103 mm/60cm
Zone 3	39	Poorly drained, deep clayey soil	16–28	118 mm/60cm
Zone 4	20	Impeded drainage, peaty topsoil, stony, shallow	24–55	66 mm/60cm

Table 2. Yield data for VRI trials at Site 1 and Site 2 (± 1 standard deviation).

Site	Crop	Zone	Treatment	Yield (t DM/ha)	Irrigation applied (mm)	Rainfall during irrigation season (mm)
1	Wheat	1	URI	4.3 ± 0.9	86	425
			VRI	5.2 ± 0.4	86	
		2	URI	5.8 ± 1.0	86	
			VRI	6.5 ± 0.8	46	
		3	URI	2.9 ± 2.2	86	
			VRI	5.8 ± 1.7	22	
2	Beans	1	URI	6.3 ± 1.7	405	225
			VRI	5.9 ± 1.0	405	
		2	URI	6.0 ± 0.1	405	
			VRI	3.5 ± 1.3	363	
		3	URI	5.1 ± 2.5	405	
			VRI	8.1 ± 0.1	341	
	Wheat	2	URI	10.4 ± 0.8	420	
			VRI	9.2 ± 1.1	420	
		3	URI	8.9 ± 0.1	420	
			VRI	10.1 ± 0.7	396	

An analysis of variance of the yield data indicated that there is no significant difference between the VRI and URI treatments at both sites. The yield data was collected just prior to mechanical harvesting of the crops at Sites 1 and 2 (Table 2).

At Site 1 (wheat) the irrigation season was wet, with 425 mm rain. Soil moisture monitoring indicated that Zone 3 required very little irrigation during the whole irrigation season, whereas Zone 1 and Zone 2 required some strategic irrigation during the periods of rapid growth between 30 November and 11 January. Overall water saving of 36% [55 mm] were obtained by delaying irrigation to Zone 2, with virtually no irrigation applied to the poorly draining Zone 3 (Table 2).

At Site 2, a range of crops were grown in the 111 ha under the VRI lateral irrigation system. Soil management zones 1, 2 and 3, closest to the river, were sown into faba beans. Parts of Zone 2 and Zone 3 were sown into wheat, and the upper terrace (Zone 4) was sown into a variety of seed and salad crops, including pak choi, buckwheat and corn salad. To eliminate the effect of different crop water requirements, we restricted our trials to areas where one crop was grown. Two trials were conducted (a) across Zones 1, 2 and 3, sown into faba beans, and (b) across Zones 2 and 3, sown into wheat (see Fig. 1). Statistical analysis of the yield data showed there was no significant difference in yield under the VRI and URI treatments for both crops, with water savings of 3% [13 mm] in the wheat crop and 9% [38 mm] in the bean crop. At this farm, where the restricted freshwater allocation is fully utilised in any one irrigation season, this saving equates to two additional 30 mm irrigation events to an additional 40 ha of crops.

For Site 3 the impact of irrigation treatments on pasture production is shown in Fig. 2. The regular measurements of dry matter production per hectare for each treatment plot were averaged for the whole season to obtain an estimate of average pasture cover. The results show that there was no significant difference in average pasture cover between treatments over two years of trials, and 28% [48 mm] of water was saved by employing variable rate irrigation. Good management maintained average pasture cover between 2000 and 2500 kg DM/ha for the period of study. An average pasture cover that is too low can result in slow regrowth, and if it is too high, pasture quality will decline and production will also suffer.

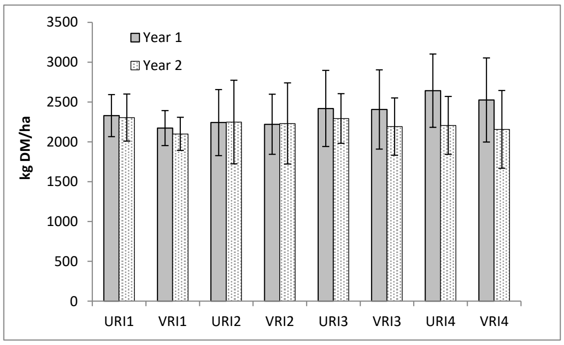

Figure 2. Average pasture cover for each treatment for 2010/2011 and 2011/2012, showing that the variable irrigation scheduling had no significant impact on yield [error bars: ±1 standard deviation].

Conclusion

The variable rate irrigation decreased water use by 27 – 55 mm per hectare at the three sites, whilst having no significant impact on yield. . The variable rate scheduling varied timing and amount of irrigation to different soil zones, delaying and/or reducing irrigation to (a) poorly drained soils and (b) soils with greater ability to store and provide water to crops. At farms where the freshwater allocation is being fully utilised, this saved water can be diverted to other crops which would otherwise not be irrigated. Further research is required at more sites, with modelling over a longer period of time, to more fully assess the potential benefits of variable rate irrigation systems.

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