Analysis of potential benefits of precision irrigation for variable soils at five pastoral and arable production sites in New Zealand

Carolyn Hedley[A], Ian Yule[B] and Stu Bradbury[C]

[A]Landcare Research, Riddet Road, Massey University Campus, Palmerston North 4474, NZ, Email hedleyc@landcareresearch.co.nz
[B]NZ Centre for Precision Agriculture, Massey University, Palmerston North, NZ, Email i.j.yule@massey.ac.nz
[C]Precision Irrigation, 581 Taonui Rd, RD5, Feilding, NZ, Email stu@precisionirrigation.co.nz

Abstract
The potential benefits of modifying irrigation according to soil differences under one irrigation system have been assessed for five production sites for the period 2004–2008. A simulated analysis used a soil water balance to compare hypothetical uniform rate irrigation (URI) with variable rate irrigation (VRI) scheduling for four irrigation seasons (2004–2008). URI applies irrigation to the whole area when the most droughty soil zone reaches a critical soil moisture deficit, whereas VRI only applies irrigation to the soil zone that has reached its critical soil moisture deficit. The method has developed digital soil water status maps from spatially located soil apparent electrical conductivity (EC_a) data regressed against soil available water-holding capacity (AWC) ($R^2 \geq 0.8$ at 4 sites), with a daily time step added using a soil water balance model (Hedley and Yule 2009). These maps are available for upload to a fully automated variable rate irrigation system (Bradbury 2009). Water-use efficiency indicators show that potential water savings with VRI are 8–21%; drainage and runoff was reduced 19–55%, and cost savings were estimated at NZ$51–NZ$150 per hectare.

Key Words
EM mapping, AWC map, soil water status, variable-rate irrigation.

Introduction
Precision irrigation of variable soils is a soil-based strategy for improved use of global freshwaters and soils, addressing global food security issues, because agriculture accounts for 70% of global water use and more than a third of the world's food requires irrigation for production (Goodwin and O'Connell 2008). Such strategies to conserve natural capital, are required to meet the 21st century's global food security challenge (Lal 2009).In New Zealand, sprinkler systems now compose at least 40% of all irrigation systems, and often traverse highly variable soils (e.g. the silty, sandy and stony soils of the Canterbury Plains). Therefore studies were initiated to investigate the potential benefits of a soil-based decision support tool for variable rate irrigation of variable soils (Hedley and Yule 2009). In addition, Bradbury (2009) has developed a variable rate modification of existing sprinkler systems that fits each sprinkler with a latching solenoid valve that is pulsed either on or off by a node. Each node is part of a wireless network: it provides individual control of four sprinklers and receives wireless inputs from a central controller to guide variable water delivery (Bradbury 2009). New Zealand uptake of this technology has been for several reasons; and once installed these VRI systems have multiple benefits including control of soil water status in the optimum range for plant growth. The system differs from the air-actuated valve VRI system of Han et al. (2009), also described by Perry *et al*. (2002), because it does not require a compressed air-line, and every sprinkler is controlled individually. The New Zealand VRI customised software allows upload of the soil water status maps developed for spatial irrigation scheduling (Hedley and Yule 2009).VRI is best suited to centre pivot and lateral sprinkler irrigation systems, which have high application accuracy, and sprinkler line design well suited to individual sprinkler control. Other forms of irrigation, such as drip irrigation, are used where water is more severely limited, and/or land productivity is less, and there are potential applications for similar support tools for these systems. This research paper uses water use efficiency indicators to analyse potential benefits of VRI scheduling on variable soils at five production sites.

Methods
Site Selection
The five sites were:

- Site 1: 156 ha Manawatu pastoral site on alluvial and high terrace loessial soils
- Site 2: 40 ha Canterbury dairy pastoral site on alluvial outwash gravelly soils
- Site 3: 22 ha Manawatu maize grain crop on sand plain and dune soils
- Site 4: 35 ha Manawatu maize grain crop on alluvial terrace soils
- Site 5: 24 ha Ohakune potato crop in mixed volcanic air-fall and water-borne tephric soils

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EMI survey and soil EC_a map production, with characterization of soil zone AWC

An on-the-go electromagnetic induction (EMI) mapping system was used to collect simultaneous high resolution (≤ 12 m) positional and soil apparent electrical conductivity (EC_a) data. Each EC_a map was then used for field investigation of soil differences, and on the basis of these differences, topography and practical management implications, the EC_a zones were divided into a smaller number of soil management zones (3−4), using Geostatistical Analyst (ArcGIS, ESRI). Soil samples were collected from each of these zones (≥ 3 replicates) to characterize zone AWC (defined as the soil moisture difference between field capacity [FC] and wilting point), (Hedley and Yule 2009).

Hypothetical irrigation scheduling for VRI and URI

A soil water balance model (Allen *et al*. 1998) was used to track soil wetting and drying patterns of individual soil management zones, for updating the AWC maps. Model inputs are: AWC, evapotranspiration (Et), capillary rise, rainfall and irrigation. The model determines root zone soil water depletion relative to FC (mm), on any one day. Site-specific rainfall was used, and reference Et was estimated using the FAO Penman-Monteith equation for a uniform grass sward. Reference Et was adjusted for crop type and stage at the irrigated maize and potato sites to provide crop Et. A dual coefficient model for crop Et was used, which assesses soil evaporation separately from crop transpiration. This is important under the frequent irrigation events which continually rewet the soil surface. Capillary rise, C, was assumed to be zero when the water table was >1m below the base of the root zone. Otherwise its contribution was calculated (Scotter 1989) and added to AWC to provide an effective AWC (EAWC). Irrigation events (10 mm) were scheduled on the day that zone critical soil moisture deficit (CSMD) for irrigation was reached (depletion factor of 0.5AWC [pasture]; 0.55AWC [maize]; 0.35AWC [potatoes]). URI scheduled an irrigation event (10 mm) to the whole area when the zone with smallest AWC reached its CSMD. VRI scheduled irrigation events to specific zone CSMD, making better use of soil profile water storage, and also maintaining potential yield.

Water use efficiency (WUE) indicators

The following WUE indicators were used to assess the potential benefits of VRI compared with URI:

Amount of irrigation water used (mm/season)

Amount of drainage and runoff during the period of irrigation and whole year (mm/season)

Cost saving (based on a typical cost of irrigation: NZ$2/mm/ha; FAR 2008).

Irrigation water-use efficiency (IWUE) is calculated as the kg of increased dry matter production ($Yield_{irrig}$ – $Yield_{non-irrig}$) per mm of irrigation water applied. Actual or typical regional yields have been used in this calculation.

Energy use is calculated as kg CO_{2-eq}/m^3 of irrigation water applied. A factor of 0.50 kWh/m^3 irrigation water pumped is used based on data reported in New Zealand literature (e.g. FAR 2008). The conversion factor of 0.18 is then used to convert kWh to kg CO_{2-eq} (MED 2008).

Nitrogen leaching was estimated at three sites using the nutrient budgeting model Overseer Version 5.4.3 (AgResearch® 2009) for pasture, and biophysical models AMaizeN (Li 2006) and The Potato Calculator, (Jamieson *et al*. 2004). These models simulate crop growth using site-specific climate, soil and crop production inputs; with N leaching below the root zone (kg N/ha) being one output. The depth of the root zone was set at 0.6 m for pasture and potatoes, and 1.5 m for maize.

Results

Significant differences in zone AWC were found at all sites (Table 1). Soil AWC was regressed against soil EC_a at Sites 1-4 ($R^2 \geq 0.8$), and prediction models were developed to produce soil AWC maps. Soil EC_a is controlled by soil moisture and texture differences at Sites 1 and 4. At Site 2, soil EC_a is controlled primarily by percent stones. At Site 3, it reflects soil moisture differences, with capillary rise supplying additional water for plant use in Zone 2 and 3. The amount of additional water supplied above AWC was estimated using a relationship developed by Scotter (1989) for these sand soils. At Site 5, a field investigation of the EC_a-defined soil zones revealed three distinctly different soil parent materials in a complex soil pattern of air-fall and water-borne volcanic materials. At this site, soil AWC was significantly different between zones (Table 1), so that zone management could be used for irrigation scheduling.

Table 2 gives AWC range at any one site and reports a summary of comparisons of WUE indicators for URI and VRI. The amount of irrigation water saved using VRI varied between 8 and 21% per year (mean of 4 years, 2004–2008) being greatest at Site 3, where additional water is contributed via capillary rise from a seasonally high water table at different rates to the different zones (Table 1). VRI conserves more water in

Table 1. Soil texture and effective AWC of EC_a-defined zones (standard deviation in brackets, n=3).

Site	Soil texture	EC_a (mS/m)	Capillary Rise (CR) (mm)	EAWC (AWC + CR)* (mm root/zone)
Site 1 – Manawatu pasture (on Alluvial and High terraces soils)				
Zone 1	Loamy gravel	14.0–20.0	0	77 (9) a
Zone 2	Sandy loam	20.0–30	0	99 (6) a b
Zone 3	Silt loam	30.0–37.0	0	124 (28) b c
Zone 4	Silt loam	37.0-65.0	0	132 (16) c
Site 2 – Canterbury dairy pasture (on Alluvial terrace soils)				
Zone 1	Very stony sandy loam	12.5–13.6	0	44 (6) a
Zone 2	Stony sandy loam	13.7–14.6	0	74 (19) a
Zone 3	Sandy loam	14.7–16.7	0	101(6) b
Site 3 – Manawatu maize grain (on Sand plains and dune soils)				
Zone 1	Sand	17.0–26.0	0	85 (6) a
Zone 2	Sand	27.0–33.0	34	214 (15) b
Zone 3	loamy sand	34.0–50.0	139	329 (17) c
Site 4 – Manawatu maize grain (on Alluvial terrace soils)				
Zone 1	Loamy sand	14.0–19.6	0	190 (10) a
Zone 2	Silt loam	19.7–22.1	0	180 (15) a
Zone 3	Mottled silt loam	22.2–27.5	0	105 (21) b
Site 6 – Ohakune potato field (in mixed volcanic air-fall and water-borne tephric soils)				
Zone 1	Loamy silt	14.9–17.2	0	186 (3) a
Zone 2	Loamy sand	17.3–18.1	0	81 (12) b
Zone 3	Sandy loam	18.2–22.9	0	156 (16) c

( ) standard deviation in parentheses; *EAWC with different letters are sig. diff. at any one site ($p \leq 0.5$)

years when there is more rainfall during the period of irrigation. A wet Spring in 2006 (1/10/06 – 31/12/06) delivered 400 mm of rain to the maize grain sites, and water savings from VRI increased from the mean of 21% to 26% at Site 3, and from 12% to 14% at Site 4. Runoff (overland) and drainage (below the root zone) savings with VRI were considerable (8–26% per year; 19–55% during the period of irrigation), because delayed irrigation to some zones allows soils to reach greater soil moisture deficits with less likelihood of runoff and deep drainage. This is indicated by an improved IWUE (Table 2).

Table 2. A comparison of VRI and URI WUE indicators.

Site	Land use	EAWC range[A] mm	Irrigation water saved %	Drainage/Runoff saved during period of irrigation %	Energy saved kg CO_2-eq/ha/y	Improved IWUE kg/mm/ha	Reduced N leaching kg/ha
1	Pasture	77–132	8	19	23	2	-
2	Pasture	44–101	9	55	40	1	3
3	Maize grain	85–329	21	40	67	5	0
4	Maize grain	105–190	12	22	38	2	-
6	Potatoes	81–186	15	29	30	4	2.5

[A]EAWC = AWC + CR; EAWC range calculated for a root zone depth of 60 cm (pasture, potatoes) and 100 cm (maize grain).

Our N leaching models support the reduced drainage data under potatoes and pasture with VRI. The amount of leached N per year under dairy pastoral systems was reduced with VRI (VRI: 26 kg/ha; URI: 29 kg/ha) but is overall slightly higher than for the other two systems (maize grain VRI: 22 kg/ha; URI: 22 kg/ha; potatoes VRI 9.4 kg/ha; URI 11.9 kg/ha).

Energy savings with VRI were 23–67 kg $CO_{2\text{-eq}}$/ha/y. Saved water can be diverted elsewhere when total water allocations are restricted allowing improved overall on-farm IWUE. Assuming that it costs NZ$2/ha to pump one mm irrigation water (FAR 2008), these five case studies show a cost saving of NZ$51–150/ha.
In this study, the potential water savings and accompanying energy savings with VRI, increase with soil variability, where soil variability is defined as AWC range under one irrigation system (Figure 1). Our results suggest that where the ability of the soil to store and supply water to plants varies by about 50 mm then the potential water savings are about 8.5%; and by >100 mm gives a potential water saving of ≥15%.

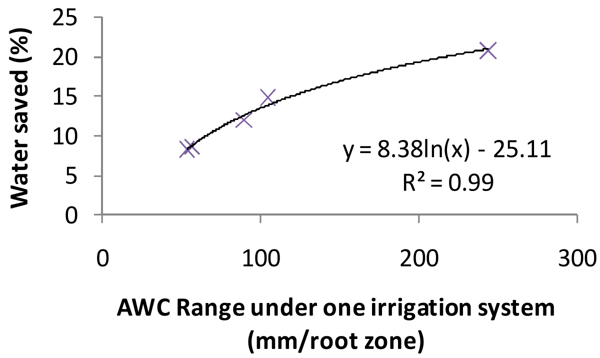

Figure 1. Relation of water saved using VRI to soil variability (defined as the difference between the smallest and largest soil AWC at each site) for five sites and a 4-yr period of study (2004–2008).

Conclusions

Increased dependence on irrigation for global food supply, and reduced availability of the global freshwater resource require irrigation systems to become increasingly more efficient. Variable soils ideally require variable timing and placement of irrigation for most efficient water use, and a precision irrigation method has been reported and assessed which schedules irrigation according to soil differences. The soil water status maps, derived from soil EC_a maps, are available for upload to a fully automated variable rate irrigation system, enabling improved water and energy use efficiency.

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