Drewry, J.J., Hedley, C., Sharp, J., Thomas, S., Wallace, D., El-Naggar, A., Roudier, P., Ekanayake, J., and Clothier, B. 2022. Improving irrigation efficiency using soil water management and proximal soil sensing. In: Adaptive Strategies for Future Farming. (Eds. C.L. Christensen, D.J. Horne and R. Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 34. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand. 9 pages

IMPROVING IRRIGATION EFFICIENCY USING SOIL WATER MANAGEMENT AND PROXIMAL SOIL SENSING

JJ Drewry[1], CB Hedley[1], J Sharp[2], S Thomas[2], D Wallace[3], A El-Naggar[4], P Roudier[1], J Ekanayake[5], B Clothier[6]

[1] *Manaaki Whenua – Landcare Research, Private Bag 11052, Palmerston North*
[2] *Plant & Food Research, Private Bag 4704, Christchurch Mail Centre*
[3] *Foundation for Arable Research, PO Box 23133, Christchurch*
[4] *AgResearch Invermay, Private Bag 50034, Mosgiel*
[5] *Manaaki Whenua – Landcare Research, PO Box 69040, Lincoln*
[6] *Plant & Food Research, Private Bag 11600, Palmerston North*

Abstract

This paper summarises research findings on improving irrigation management on variable soils through the use of proximal sensor surveys, improved irrigation strategies (including the use of soil water deficits), soil moisture monitoring, and the development of modelling approaches. We present key areas of the research, take-home messages, and practical outcomes from several field trials and case studies. A key focus is variable rate irrigation (VRI) systems, because when these systems are well designed and managed they can increase water-use efficiency, reducing the negative environmental impacts of drainage and nutrient loss to fresh waters.

Proximal soil sensing (electromagnetic and gamma), with ground-truthing, were used to map soil variability and statistically delineate zones, then available water capacity was measured for each zone. We produced management zone maps for six irrigated case study sites. These zone maps were then interpreted into a grid. A spatial-APSIM (Agricultural Production Systems sIMulator) framework was developed, which modelled production as well as environmental outcomes across the grid, constrained by the availability and capacity of an irrigator.

The research showed that managing irrigation to avoid completely refilling the soil profile (deficit irrigation) provides several environmental and financial benefits. Allowing a deficit enables rainfall to be captured while reducing the need for irrigation and decreasing the risk of drainage and nutrient leaching losses, without affecting yield. Where variable soils exist, there is a yield penalty with too much irrigation, such as on poorly drained soils, or with too little irrigation on other soils, and this can be managed using a VRI system. VRI and deficit irrigation strategies are not necessarily separate things, as deficit irrigation can be applied within a VRI system. Where variability is significant, effective deficit irrigation requires an irrigation system that can vary irrigation to each zone to maintain the required deficit. The maximum benefits for maintaining soil water deficits are often achieved in the spring and autumn periods, when irrigation systems can meet crop evaporative demand. The development of wireless sensor networks to send data to software tools was also used for adaptive irrigation management to provide high-resolution information on soil moisture to farmers.

The spatial-APSIM modelling of soil variability showed that variable rate irrigation resulted in less application of irrigation compared with uniform irrigation, with no difference in crop yield when there was high variability in soil water holding capacity. Uniform irrigation, with a soil

moisture sensor placement in the zone with the lower soil water holding capacity, was compared with soil moisture sensors placed in all zones. Uniform irrigation with the sensors in all zones resulted in less irrigation being applied with no difference in yield.

Introduction

Practices and technologies developed for precision agriculture, such as the use of management zones for the improved management of irrigation water, variable rate application of irrigation water, coupled with good farm practices, can help reduce farm nutrient inputs, improve water and nutrient use efficiency, improve crop and pasture yields, increase farm profitability, and help minimise water and nutrient losses from farms (El-Naggar et al. 2020; González Perea et al. 2018; Hedley et al. 2009; O'Shaughnessy et al. 2019). Management zones, for example, can be used for different crops in mixed cropping systems, or for different soils, or a combination of both. In some areas, such as North Otago, management zones can be defined by slope and aspect.

Within-field delineation of zones aims to simplify the spatial representation of within-field variability (Roudier et al. 2011), and operational technologies are now readily available for zone-specific management. However, before implementation, the relative benefits of zone-specific management compared with a default uniform management should be considered. Variable rate irrigation (VRI) systems have been developed for spatially variable soils, and have been shown to reduce drainage and nutrient losses compared with uniformly applied irrigation water (González Perea et al. 2018; Hedley et al. 2009; Hedley 2015; McDowell 2017).

Improving practices and tools, such as precision irrigation scheduling (including the use of deficit irrigation), as well as the development and use of sensors and sensor feedback, can improve the use of limited water resources to increase crop yields and the impact of VRI (Barker et al. 2018; Drewry et al. 2019; El-Naggar et al. 2020; O'Shaughnessy et al. 2020). Under a VRI system on a mixed cropping farm, for example, El-Naggar et al. (2020) showed that a sensor-based irrigation scheduling method used less water, and improved water use efficiency, compared with a soil water balance method.

VRI enables zone management (such as for several crops or soil types), and then different irrigation strategies (e.g. deficit irrigation can be customised to each zone). It is important to note that VRI and deficit irrigation strategies are not necessarily separate things. VRI enables improved use of deficit irrigation when more than one management zone is identified in the area to be irrigated.

Farmers need new tools that enable improvements in water usage and monitoring to enable improvements in productivity and reduced environmental impacts. As part of this project, near real-time soil moisture measurements using wireless sensor networks were developed for use in soil management zones. Such soil water monitoring networks can provide farmers with high-resolution spatial and temporal soil water status to schedule irrigation wisely (Drewry et al. 2019; Ekanayake & Hedley 2018).

This paper summarises and reviews selected components from a recent irrigation research programme and provides key messages to users and stakeholders. Several components are presented, along with APSIM modelling specifically developed to support field components and to answer key questions. This paper discusses the use of zones to better manage soil variability, modelling the impact of variability, improved irrigation management through deficit irrigation, soil moisture monitoring, and modelling soil moisture sensor placement.

Variability of case study soils

Zone-specific management

A quantitative method to assess the relative benefits of zone-specific management is provided by Roudier et al. (2011) by considering the relevant economic, environmental, and technical criteria. The method considers operational conditions in which zoning is applied, together with its associated risks, and compares this with uniform management (the null hypothesis). We applied some concepts from this method to several focus farm sites.

Table 1 provides relevant criteria for zone-specific (i.e. within-field) irrigation management. Many economic and environmental criteria vary within the cycle of one irrigated cropping season (e.g. soil moisture). This requires a scheduling decision support system capable of predicting and reacting rapidly to changes. Soil type and topography changes are less ephemeral, and rapid sensor survey methods can be used to delineate zones of this in-field variability, which can then be used as management zones (e.g. Rodrigues et al. 2015; El-Naggar et al. 2020).

Table 1. Criteria to consider when assessing the relevance of within-field irrigation management practices

Economic	Environmental	Technical
Changing the value of crop/s during the season	Soil differences	The spatial footprint of machinery
Mixed cropping under one irrigation system	Topographic differences	The ability of machinery to change from one rate to another
Sequential cropping *	Impacts of climate (e.g. poor drainage/flooding, light soils/drought, or heat stress)	The ability of machinery to accurately apply prescribed depths
Cost of water	Suitability of different crops for irrigation	

* An example of sequential cropping would be potatoes and salad crops in a market garden.

The importance of soil variability frequently outweighs topographic differences. However, there are some exceptions, such as in North Otago and South Canterbury, where slopes >16° are irrigated, increasing the likelihood of runoff. Here topography can become the major factor to be considered when designing and implementing irrigation methods (Langer et al. 2020; 2021). Technical criteria are important, including the ability of the machinery to vary inputs spatially and temporally at the required accuracy and precision.

Table 2 presents details of the focus farm irrigated trial sites. The irrigation systems ranged from the manual shift of movable irrigation lines, through automated linear and pivot sprinkler systems, to fully automated pivot with variable rate control. The variable rate irrigation system at site 1 is an integrated software–hardware system designed to schedule and control individual VRI sprinklers (http://www.myfieldnet.com/fieldnet-advisor). It automatically generates prescription maps that are dynamically optimised daily using a soil water balance modelling approach to vary irrigation in each zone.

The prescription maps utilise the zone maps derived from proximal soil sensor survey data, and they were ground-truthed by detailed pedological survey (A. Manderson, J. Payne pers. comm.). During the trial period, different crops were grown together under one system, so soil–crop combinations were applied to each zone to derive the daily prescription maps. At site 1, the VRI system irrigated up to six different crops, grown simultaneously into five different soil zones, each with different irrigation requirements. Our research focused on the development of new, proximal soil-sensing methods to map soil zones and then monitor soil moisture in near real time within each zone.

Table 2. Specifications of the irrigated trial sites

Site	Location	Land use	Irrigation system	Irrigation control	Length (m)	Irrigated area (ha)	No. of zones
1	Hawke’s Bay	Mixed cropping	VRI pivot*	Speed and individual sprinkler	552	102	5
2	Hawke’s Bay	Mixed cropping	Towable pivot	Speed	240	33	3
3	Hawke’s Bay	Mixed cropping	Pivot	Speed	635	127	3
4	Manawatū	Vegetable production	Movable lines	Manual	-	20	2
5	Canterbury	Mixed cropping	Linear	Speed	514	72	3
6	Canterbury	Mixed cropping	Linear	Speed	396	127	1
7	Canterbury	Mixed cropping	Pivot	Speed	498	31	2

* VRI = variable rate irrigation

Note: the wetting diameter of nozzles (except at site 4) ranged between 12 and 22 m.

Proximal soil sensor surveys

Proximal soil sensors enable high-resolution (<10 m) soil data to be collected rapidly and affordably when combined with accurate GPS on mobile systems. The sensors respond to variations in soil features, and the data can be used to predict key soil properties for environmental and agricultural issues (Coulouma et al. 2016). The two sensors used in this study were (1) an electromagnetic sensor, which responds to soil moisture and texture differences in non-saline soils to depths of 1.5 m, and (2) a gamma sensor, which detects gamma ray photons that are naturally emitted by certain elements occurring in soil minerals, from the upper 0.5 m of soil. The gamma sensor data indicate parent material differences and age of soil (Hedley et al. 2016).

The zone maps were derived in R (R Core Team 2014) using geostatistical methods and the electromagnetic and gamma data. Electromagnetic and gamma radiometric data were interpolated into regular 5 m resolution grids using ordinary kriging. These were then used to derive zone maps using unsupervised clustering. All computations were done in R (R Core Team 2014); further details are described in Hedley et al. 2016). The resulting maps were subsequently used for the APSIM modelling exercises reported in this paper. One aim of the APSIM modelling exercise was to compare zone management with uniform management for the trial sites.

Note that the programme did not define an overarching rule for how much soil variability is needed to implement VRI, since this was evaluated on a case-by-case basis using the trial sites. Management soil zones were defined based on the proximal soil sensor surveys. Further information on management zones derived by proximal sensing surveys is available in El-Naggar et al. 2020, 2021.

Modelling the impact of variability with a spatial-APSIM framework

The systems model used in this study was APSIM Next Generation. A spatial framework for APSIM was developed that could capture the variability in soil, the key aspects of cropping systems, and irrigation application (Sharp & Hedley 2018). The modelling framework included cropping under a single irrigator with constrained water and infrastructure availability. The case study sites with different soil variability were modelled over 35 years, with a range of climate data, for maize and potato crops.

VRI was compared with uniform irrigation, and resulted in less irrigation applied at the sites with high variability in soil water holding capacity. There were no differences in yield, but there was an increase in gross margins in maize, and no difference in potato gross margins. The modelling showed an associated decrease in drainage and an increase in water-use efficiency. Overall, the variability in site profile available water storage determined the magnitude of the impacts.

Improved irrigation management

Understanding available water capacity

Managing soil water availability in soils with low water-holding capacity is challenging (e.g. in shallow, stony soils). With limited storage it is important that as much capacity as possible is preserved through good soil management. For example, some improvements may be possible to enhance or ameliorate storage capacity through additions such as compost, because compost particles affect soil porosity (Wallace et al. 2020). Cultivated soils have the added complication of hydraulic properties such as available water capacity changing within a growing season (Drewry et al. 2021).

Deficit irrigation from field trials

Managing irrigation well to avoid completely refilling the soil profile (deficit irrigation) provides several environmental and financial benefits. Allowing a deficit enables rainfall to be captured, reducing the need for irrigation and the risk of nutrient leaching losses. Based on modelling different deficit irrigation strategies for a range of soils and climates, Vogeler et al. (2019) showed that nitrogen losses can be reduced by less frequent irrigation and maintaining deficits, with little effect on production. They predicted losses in the order of 5–6% for the shallow soils with the most extreme deficit treatments.

They also found that most nitrate leaching was predicted from shallow soils, but this amount could be almost halved by maintaining large deficits. This supports findings from a previous study, where better management of irrigation through large deficits reduced nitrate leaching with good nitrogen fertiliser management (Francis et al. 2007). Maintaining soil water deficits in the surface soil reduces nitrous oxide emissions and the risk of compaction. Soil compaction also increases the risk of nitrous oxide emissions, and nutrient and production losses (Hu et al. 2021).

Where on-farm water allocation is limited, a soil water deficit may allow growers to use water more strategically at critical crop development stages. A potential issue when generating soil water deficits is the potential build-up of soil water repellency, which may reduce the water infiltration speed or the amount of water storage (Müller et al. 2016).

The maximum benefits for maintaining soil water deficits are often achieved in the spring and autumn periods, when irrigation systems can meet or exceed crop evaporative demand. During periods of peak evaporation during summer, deficits may develop because irrigation systems are unable to keep up with plant water requirements due to water allocation limitations, water restrictions or system constraints.

In a case study at a cropping farm with variable soils (site 2, Table 2), for example, soil water monitoring of three management zones showed that the poorly drained soil had wetter conditions than the other zones, which is likely to have been a factor contributing to reduced barley yield (Drewry et al. 2019). The poorly drained soil was more often near to or at saturation compared with the other soils, whereas the other, freer-draining soils zones often had a soil water deficit. Less irrigation could therefore have been applied to the poorly drained soil, with a saving in cost and yield penalty (Drewry et al. 2019).

Variability in soil horizons and available water capacity

In order to apply appropriate irrigation management, spatial variability in soil water patterns down the soil profile and across the landscape needs to be determined. Real-time, sensor-based, and soil-water balance irrigation scheduling methods were compared on a VRI irrigated mixed cropping farm. El-Naggar et al. (2020) showed that the sensor-based scheduling method delivered 27–45% less water compared with the soil water balance method, which calculated daily soil water deficits.

The sensor-based scheduling was used for pea and bean crops via a wireless soil moisture sensor network. Soil moisture sensors were placed at four soil depths. Soil water deficit values for each of the two soils (Manawatū fine sandy loam and Manawatū silt loam) were determined using laboratory measurements of available water capacity. Differences in available water capacity between the soils became apparent below 0.2 m.

The spatial variability of soil water patterns was attributed to the influence of varying soil properties such as texture and drainage characteristics (El-Naggar et al. 2021). The soil water balance irrigation scheduling method produced similar pea crop yields but did not account for the restricted drainage at depth in the silt loam. Differences in the amount of water saved were also attributed to the use of VRI and avoiding the silt loam becoming water-logged. (Further details are available in El-Naggar et al. 2020, 2021.)

Soil moisture monitoring and wireless sensor networks

Technological development over the last 30–40 years has advanced wireless sensor networks so that they can now provide high-resolution information on soil moisture for effective strategic decisions by land managers. Modern wireless sensor networks use sensors installed in the field that communicate via a ‘gateway’ (a physical device or software program) that acts as a data-relaying point to cloud storage and databases where data are processed into spatial information (e.g. soil water status; Ekanayake 2021; Ekanayake & Hedley 2018). By visualising soil moisture data in real time, farmers can use these tools for precision irrigation scheduling to increase their water-use efficiency.

Phone apps and other near real-time soil moisture data visualisations indicating when to irrigate and when to stop were developed for case study farmers. (Further details are available in Ekanayake & Hedley 2018 and Drewry et al. 2019.) It is useful to monitor a range of depths in and below the root zone; a sensor below the root zone can indicate whether irrigation is causing drainage.

Modelling soil moisture sensor placement with a spatial-APSIM framework

As earlier described in this paper, a spatial framework for an existing systems model (APSIM) was developed (Sharp & Hedley 2018). The modelling framework included cropping under a single irrigator with constrained water and infrastructure availability. The case study sites with different soil variability were modelled over 35 years, with a range of climate data, for maize and potato crops.

Uniform irrigation, with a soil moisture sensor placement in the zone with the lower soil water holding capacity, was compared with soil moisture sensors placed in all zones. Uniform irrigation with the sensors in all zones resulted in less irrigation being applied with no difference in yield. Water-use efficiency increased, and there were large decreases in drainage in some years. The magnitude of the impact was determined by the variability in site profile available water storage and mean seasonal rainfall.

Conclusions and key messages

Managing irrigation to avoid completely refilling the soil profile (deficit irrigation) provides several environmental and financial benefits. Allowing a deficit enables rainfall to be captured while reducing the need for irrigation and decreasing the risk of drainage and nutrient leaching losses, without affecting yield. Where variable soils exist, there is a yield penalty with too much irrigation, such as on poorly drained soils, or with too little irrigation on other soils, and this can be managed using a VRI system.

Implementation of deficit irrigation strategies to variable soil–crop combinations also requires a system designed to manage this, such as a VRI system. VRI and deficit irrigation strategies are not necessarily separate things. VRI enables improved use of deficit irrigation when more than one management zone is identified in the area to be irrigated. Where variability is significant, effective deficit irrigation requires an irrigation system that can vary irrigation to each zone to maintain the required deficit within each zone. The maximum benefits for maintaining soil water deficits are often achieved in the spring and autumn periods, when irrigation systems can meet crop evaporative demand.

The spatial-APSIM modelling of soil variability showed that variable rate irrigation resulted in less application of irrigation compared with uniform irrigation, with no difference in crop yield when there was high variability in soil water holding capacity. Uniform irrigation, with a soil moisture sensor placement in the zone with the lower soil water holding capacity, was compared with soil moisture sensors placed in all zones. Uniform irrigation with the sensors in all zones resulted in less irrigation being applied with no difference in yield.

Further resources

Further resources and case studies are available via video and a story map:
MVI - Maximising the Value of Irrigation - YouTube
https://bit.ly/2L0MCdO

Acknowledgements

Thanks to the farmers for participating, and providing access and information. Thanks to Balin Roberston and Shana Dooley for comments on a draft, and Ray Prebble for editing. Principal funding for the research was provided by the New Zealand Ministry of Business, Innovation and Employment for the Manaaki Whenua – Landcare Research and Plant & Food Research-led programme 'Maximising the Value of Irrigation' (contract CO9X1309). Co-funding was provided from the Foundation for Arable Research, Horticulture New Zealand, Environment Canterbury, Hawke's Bay Regional Council, and Irrigation New Zealand.

References

Barker JB, Heeren DM, Neale CMU, Rudnick DR 2018. Evaluation of variable rate irrigation using a remote-sensing-based model. Agricultural Water Management 203: 63–74.

Coulouma G, Caner L, Loonstra EH, Lagacherie P 2016. Analysing the proximal gamma radiometry in contrasting Mediterranean landscapes: towards a regional prediction of clay content. Geoderma 266: 127–135.

Drewry JJ, Hedley CB, Ekanayake J 2019. Maximising the value of irrigation through improved use of soil resources and sensor technology. Journal of New Zealand Grasslands 81: 223–230. https://doi.org/10.33584/jnzg.2019.81.376

Drewry JJ, McNeill SJ, Carrick S, Lynn IH, Eger A, Payne J, Rogers G, Thomas SM 2021. Temporal trends in soil physical properties under cropping with intensive till and no-till management. New Zealand Journal of Agricultural Research 64: 223–244.

Ekanayake J 2021. Advances in wireless sensor network communications – using garage-door remotes in the 1990s to satellites in 2021. Soil Horizons 30. https://www.landcareresearch.co.nz/publications/soil-horizons/

Ekanayake JC, Hedley CB 2018. Advances in information provision from wireless sensor networks for irrigated crops. Wireless Sensor Network 10(04): 71–92.

El-Naggar AG, Hedley CB, Horne D, Roudier P, Clothier BE 2020. Soil sensing technology improves application of irrigation water. Agricultural Water Management: 105901.

El-Naggar AG, Hedley CB, Roudier P, Horne D, Clothier BE 2021. Imaging the electrical conductivity of the soil profile and its relationships to soil water patterns and drainage characteristics. Precision Agriculture 22: 1045–1066.

Francis G, Thomas S, Barlow H, Tabley F, Gillespie R 2007. Management strategies to minimise nitrate leaching losses from arable soils. Fertilizer and Lime Research Centre, Massey University, Palmerston North.

González Perea R, Daccache A, Rodríguez Díaz JA, Camacho Poyato E, Knox JW 2018. Modelling impacts of precision irrigation on crop yield and in-field water management. Precision Agriculture 19: 497–512.

Hedley C 2015. The role of precision agriculture for improved nutrient management on farms. Journal of the Science of Food and Agriculture 95: 12–19.

Hedley CB, Roudier P, Peterson P 2016. Gamma soil surveys – investigating soil patterns for nutrient and water management. In: Currie LD, Singh R (Eds.), Integrated Nutrient and Water Management for Sustainable Farming. http://flrc.massey.ac.nz/publications.html. Occasional Report No. 29. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Hedley CB, Yule I, Tuohy MP, Vogeler I 2009. Key performance indicators for simulated variable-rate irrigation of variable soils in humid regions. Transactions of the American Society of Agricultural and Biological Engineers 52: 1575–1584.

Hu W, Drewry J, Beare M, Eger A, Müller K 2021. Compaction induced soil structural degradation affects productivity and environmental outcomes: a review and New Zealand case study. Geoderma 395: 115035.

Langer S, Cichota R, Thomas S, George M, Cummins M, Johns T, Dodson M, Hayman R 2021. Improving irrigation management on hillslope pastures. Journal of New Zealand Grasslands 83: 135–144.

Langer S, Cichota R, Thomas S, Wallace D, van der Klei G, George M, Johns T, Almond P, Maley S, Arnold N, Hu W, Srinivasan MS, Rajanayaka C, Dodson M, Hayman R, Ghimire C 2020. Understanding water losses from irrigated pastures on loess-derived hillslopes. Journal of New Zealand Grasslands 82: 103–110.

McDowell RW 2017. Does variable rate irrigation decrease nutrient leaching losses from grazed dairy farming? Soil Use and Management 33: 530–537.

Müller K, Carrick S, Meenken E, Clemens G, Hunter D, Rhodes P, Thomas S 2016. Is subcritical water repellency an issue for efficient irrigation in arable soils? Soil and Tillage Research 161: 53–62.

O’Shaughnessy SA, Kim M, Andrade MA, Colaizzi PD, Evett SR 2020. Site-specific irrigation of grain sorghum using plant and soil water sensing feedback – Texas High Plains. Agricultural Water Management 240: 106273.

O’Shaughnessy SA, Evett SR, Colaizzi PD, Andrade MA, Marek TH, Heeren DM, Lamm FR, LaRue JL 2019. Identifying advantages and disadvantages of variable rate irrigation: an updated review. Applied Engineering in Agriculture 35(6): 837–852.

R Core Team 2014. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Rodrigues FA, Bramley RGV, Gobbett DL 2015. Proximal soil sensing for precision agriculture: simultaneous use of electromagnetic induction and gamma radiometrics in contrasting soils. Geoderma 243–244: 183–195.

Roudier P, Tisseyre B, Poilve H, Roger J-M 2011. A technical opportunity index adapted to zone-specific management. Precision Agriculture 12: 130–145.

Sharp J, Hedley C 2018. Application of a systems model to a spatially complex irrigated agricultural system: a case study. Proceedings of the 14th International Conference on Precision Agriculture. Montreal, Canada, International Society of Precision Agriculture. Pp. 1–9.

Vogeler I, Thomas S, van der Weerden T 2019. Effect of irrigation management on pasture yield and nitrogen losses. Agriculture Water Management 216: 60–69.

Wallace D, Almond P, Carrick S, Thomas S 2020. Targeting changes in soil porosity through modification of compost size and application rate. Soil Research 58: 268–276.