FAR FOCUS

Foundation For Arable Research

Issue 04 August 2010

Irrigation Management for Cropping - A Grower's Guide

ISSUE 4

- Why is Good Irrigation Management Important?
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- Pulling these Factors Together
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- Improving Water Use on Farms

FAR would like to acknowledge the funding support of

Sustainable Farming Fund
Ministry of Agriculture and Forestry
Te Manatū Ahuwhenua, Ngāherehere

Horticulture New Zealand

Background

This FAR Focus edition is part of a three year Foundation for Arable Research (FAR) and MAF Sustainable Farming Fund (MAF SFF) funded project titled “Improving Irrigation Management of Arable and Vegetable Crops”. The project has included; seminars, field days, FAR Arable Updates, irrigator evaluation case studies and the development of an irrigation scheduling software tool for arable crops, AquaTRAC™.

This booklet presents guidelines for optimal irrigation management of crops. It provides background on how plant and soil factors influence irrigation requirements and then provides practical detail on how to schedule irrigation, select a soil moisture meter and assess irrigator performance. Helpful tips are displayed in boxes throughout this booklet.

The booklet doesn’t cover irrigation system design. However, Irrigation New Zealand has developed an irrigation code of practice and irrigation design standards. This can be found at www.irrigationnz.co.nz/publications/code-of-practice

This project was jointly funded by the MAF Sustainable Farming Fund, FAR and Horticulture NZ

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Ministry of Agriculture and Forestry
Te Manatū Ahuwhenua, Ngāherehere

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Contents

1. Checklist

Know your crop

- Maximum root depth (in the absence of impediments)
- Root growth rate and time to reach maximum root depth
- Crop cover

Know your soil

- Available water capacity of upper soil layer
- Stone content of upper soil layer
- Depth to gravel layer
- Root impediments (cultivation pans and compact subsoils)

Determine key parameters for each paddock

- Available water capacity (available water to the crop's root depth)
- Trigger point - about 50% of available water capacity
- Refill amount (how much water should be applied by irrigation?)

Evaluate distribution uniformity of irrigator

Effective irrigation aims to keep soil water content (SWC):

- Above trigger point so yield is not being lost
- Below field capacity so drainage and leaching are not occurring

Schedule irrigation by either:

- Use a scheduling service or
- Calculate soil water content with a soil water budget or
- Use a crop calculator (which provides a detailed water budget) or
- Measure your soil moisture content

Successful water scheduling using a water budget requires accurate records of:

- Rainfall - how much and when
- Irrigation - how much and when
- Evapotranspiration - from newspaper, NIWA or FAR websites or use historic averages as a close approximation

A soil water budget together with weather forecasts can estimate when the trigger point will be reached next

- SWC tomorrow = SWC today + rain + irrigation - drainage - evapotranspiration
- Drainage will occur when SWC exceeds field capacity

Soil moisture measurements may be used to indicate how close a soil is to the trigger point but consideration of root depth, soil characteristics and upcoming weather events are necessary to devise an irrigation schedule.

2. Why is Good Irrigation Management Important?

- Crop
- Environment
- Cost
- Water allocations

Crop

Ensuring crops are fully watered helps maximise yield and quality.

Environment

If too much water is applied there is a risk that nutrients will drain into ground water. On the other hand, with good irrigation management, the paddock is not irrigated to field capacity so that there is space left in the soil profile to utilise rainfall.

Cost

A recent survey showed the average capital and operating cost of irrigation was $2/mm/ha. Applying just enough water to maximise production means excess water is not pumped, therefore reducing labour and energy costs. Also, the cost of nutrient loss in drainage will be minimised. Good irrigation system design (e.g. correct pipe sizing) and maintenance will ensure operating costs are minimised.

Water allocations

As regulations are introduced, such as restricting the quantity of water to growers, it will become more important to optimise use of irrigation.

3. Factors Influencing Crop Water Supply

- Crop water demand
- Soil water supply

Crop water demand

What crops use water for

Plants are composed of 70 to 90% water and plant cells must be wet for the plant to grow and function properly. Water is taken up by the crop's root system to maintain a suitable water content in the plant. The plant has tiny pores in its leaves (called stomata) that it must open to allow carbon dioxide (CO_2) to enter for photosynthesis, the process that drives crop growth and yield. An unavoidable consequence of photosynthesis is water evaporating from the plant cells and diffusing out through the open stomata. This loss of water is called transpiration and 99% of the water taken up by the plant is lost in this way. The amount of water lost by transpiration depends on atmospheric conditions. (An increase in temperature, sunlight and windspeed all cause an increase in transpiration).

Water stress occurs when a crop's root system is unable to supply enough water from the soil to meet the demand imposed by the atmosphere. In these situations leaf water potential declines (leaves become flaccid) and stomata close to maintain a suitable water content. Stomatal closure reduces the amount of CO_2 that can enter the leaf which reduces photosynthesis. The reduction in photosynthesis causes a reduction in the crop's biomass production and subsequent yield. To maximise yields it is necessary to provide enough water to ensure water supply always meets crop demand.

Roots

Crop root depth and root architecture has an important influence on how much soil the plant can explore to extract water. The available water capacity (AWC) of a soil describes how much water can potentially be supplied by the soil for a given root depth. For a shallow rooted crop, such as peas, the AWC is less than a deep rooted crop such as autumn wheat. Thus, it is necessary to know how deep a crop's roots will go and how deep they are when the irrigation season starts. Crop roots will stop at an impeding soil layer such as stones, iron pan, cultivation pan or water table. This must be taken into account when calculating rooting depth and AWC. Provided there is no limitation to rooting depth, the maximum crop rooting depths are around 1.5 m for maize and winter cereals, 1 m for spring cereals, first year clover and first year grass seed crops and 0.8 m for peas. Crops can take two to seven months to get to these depths, therefore irrigation will need to be adjusted to account for shallower roots when the crop is young.

Provided suitable conditions prevail, plant roots can extend through the soil at rates of up to 50 cm depth per month during summer (this rate can be used for all crops but the data is most robust for cereals). This growth rate is less during winter (20 cm/month) thus crop sowing time will effect how deep the roots are at any given time. Crops sown in spring and summer will reach their maximum rooting depth faster than autumn sown crops (Table 1). The current rooting depth of your crop will affect how much irrigation you should apply and the return period. Shallow rooted crops require more frequent irrigation with less water applied each time than deeper rooted crops.

Table 1. Rooting depth (m) up to six months after sowing for a cereal crop sown at four different times

months after sowing	1 Mar	1 May	1 Aug	1 Oct
1	0.5	0.3	0.2	0.4
2	0.8	0.5	0.5	0.9
3	1.0	0.7	0.9	1.4
4	1.2	0.9	1.1	-
5	1.4	1.2	1.6	-
6	1.6	1.6	-	-

Crop cover

Crop cover influences crop transpiration and soil evaporation, collectively termed evapotranspiration. Evapotranspiration (ET) is a key element of a water budget and is reported in mm. Climatic conditions that drive ET are temperature, radiation, humidity and wind. ET rates can reach as high as 8 mm per day on hot windy days in summer. Daily ET values are often published in newspapers and can be obtained from the FAR and NIWA websites (www.far.org.nz and www.niwa.co.nz).

Evapotranspiration represents how much water will be transpired from a well watered crop that is fully covering the ground. A crop with an incomplete ground cover does not use as much water. As an approximate rule, a crop with 50% ground cover will lose water at 50% of ET, a crop with a 25% ground cover will lose water at 25% of ET and so on. The remaining portion of ET drives evaporation from the soil. A bare soil will lose water at a similar rate to ET if the soil surface is wet. So for a crop with 50% cover soon after a rainfall or irrigation event, transpiration will be 50% of ET and evaporation will be 50% of ET. However, soil evaporation quickly drops as the soil surface dries and will become negligible after a few days. For most arable crops (cereals, peas etc), the rate of water use is the same. The amount of water used by arable crops is generally not affected by crop type.

Yield response to water stress

Water stress in plants reduces stomatal opening and therefore photosynthesis. This leads to a reduction in crop growth and therefore lower yields. Water stress is influenced by soil water content (SWC). When the soil water content is close to its full point (field capacity), water supply can meet demand and a crop can grow at its maximum rate. As the soil dries, the roots can initially get enough water from the soil for the plant to continue growing at its maximum rate. However at a certain point, called the trigger point (TP), the roots can no longer extract enough water, supply will fall below demand, the crop becomes water stressed and growth decreases (Figure 1). As the soil continues drying, growth continues to decline until eventually it stops at what is often called the permanent wilting point (PWP) or lower limit.

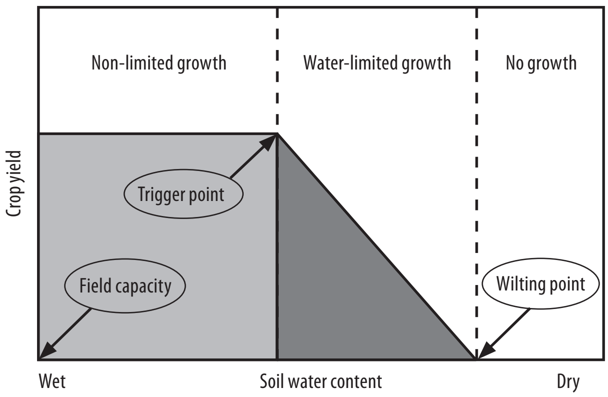

Figure 1. Diagrammatic yield responses of crops to soil moisture deficits

If soil water content is maintained above the trigger point the crop will always be growing at its optimum and yields will not be limited by water stress. Yield will be reduced below potential whenever SWC falls below trigger point. The size of the reduction increases the further the SWC falls below the trigger point and the longer the SWC remains below the trigger point. **(Any yield lost from water stress cannot be regained!)**

Table 2. Spring barley response to irrigation at the FAR Chertsey Arable Site

Year	Irrigated yield (t/ha)	Dryland yield (t/ha)	Irrigation applied (mm)	Response to irrigation (t/ha)
2009	9.0	5.1	315	3.9
2008	10.8	5.3	185	5.5
2007	8.0	8.1	80	-0.1
2006	7.5	5.4	230	2.1
2005	9.9	10.0	75	-0.1
2004	8.5	4.1	200	4.4
average	9.0	6.3		2.7

An example of actual yield decrease due to drought is shown in Table 2. At the FAR Chertsey Arable Site spring barley yield was halved on dryland compared with irrigated in two of the past six years.

Timing of irrigation in relation to crop growth stage

Does it make a difference when a water shortage occurs? In other words, does growth stage matter? Until about 35 years ago, there was a very strong feeling that there were stages of growth at which sensitivity to water deficits was much greater than others. More recent work has not supported that idea. Irrigation research in New Zealand over the past 20 years has found little evidence of critical growth stages for irrigation in most of the crops tested. An increase in the amount of water stress decreased yield and the yield reduction for a given amount of water stress was the same regardless of when it occurred. The only exceptions appear to be maize in which drought tolerance increased through the season, and white clover in which some water stress is needed at some growth stages to prevent leaves overtopping the flowers and reducing yield.

The apparent presence of critical stages (e.g. flowering in peas) can be explained by the crop's pattern of evapotranspiration demand. In hot weather a crop with full cover will lose water at a faster rate and go beyond trigger point faster than a crop with partial cover or a crop in cool weather. Therefore, any growth stage that occurs when a crop has full cover or at hotter times of the year will appear to be more sensitive to water stress. This is because the water stress arrives and increases in severity faster, not because the particular development phase is more sensitive to water stress. For the example of flowering in peas, it appears most sensitive to water stress because it occurs when the crop has full cover and at a hot time of the year. For any crop it could be said that the most sensitive stages are those when the crop has the highest evapotranspiration demand.

Soil water supply

Available water capacity (AWC)

The available water capacity (AWC) of a soil describes how much water can potentially be supplied by the soil for a given root depth. AWC is the difference between field capacity and permanent wilting point.

- Field capacity (FC) is the soil water content at its fullest point after the largest pores have drained and is the upper limit of water storage in the soil.
- Permanent wilting point (PWP) is the lower limit for crop water extraction and is the point when the growth of a crop completely stops due to water stress and is permanently wilted throughout the day.

Field capacity and permanent wilting point are measures of soil water content (SWC) and are both measured in mm. Thus AWC is measured in mm also. These three measures of soil water content (FC, PWP and AWC) are needed to calculate important factors for efficient irrigation. These include:

- The trigger point (TP), the soil water content when water stress occurs and crop growth declines. This can be estimated as 50% of available water capacity (AWC). The trigger point can be used as the soil water content at which irrigation is needed.
- Readily available water (RAW) is the amount of water in a soil between the trigger point and field capacity. If irrigating when the soil water content is at the trigger point, RAW is how much is needed to re-wet the soil to field capacity, although irrigating to field capacity is not recommended.

Soil moisture deficit (SMD) is the difference (mm) between the soil water content and field capacity. Soil water content (SWC) is the actual amount of water (mm) held in the soil. This can be estimated from a soil water budget or measured through a variety of soil moisture monitoring devices (see section 5). Given the importance of soil available water capacity in irrigation, it is important you determine AWC for your soil type. AWC is a static soil property, so determining AWC is a one-off exercise.

Most soils are layers of different materials, and the depth and type of those materials will affect AWC. To determine AWC, dig a hole to the maximum root depth and describe the depth and the textures of those layers. Use the values in Table 3 to calculate AWC.

Example 1. AWC to 1 m of a soil that is 60 cm of silt loam over gravels would be:

(160 mm/m (silt loam) x 0.6 m) + (55 mm/m (gravels) x 0.4 m) = 118 mm

Example 2. AWC to 80 cm of a soil that is 30 cm of silt loam over clay loam would be:

(160 mm/m (silt loam) x 0.3 m) + (130 mm/m (clay loam) x 0.5 m) = 113 mm

Table 3. AWC of different soil textures

Soil texture	AWC (mm/m)
Clay	110-150
Silt	155-165
Sand	65-110
Gravels	50-60
Stones	0

For each layer (other than gravels), it is important to determine the amount of stones. Stones hold no water and hence have a dilution effect on AWC. A soil that is half stones will only have half the AWC. The volume of stones can be determined by digging out a known volume of the soil layer (e.g. area of 20 cm x 20 cm and 30 cm deep), separating out the stones and measuring their volume (the easiest way is to measure how much water they displace from a full bucket). The volume of stones is expressed as a % of the total volume that was dug out.

The deeper the soil, the higher the AWC and the longer it takes to reach the trigger point (Table 4). On a shallow stoney soil (eg Lismore), irrigation is required at least weekly to prevent loss of yield in midsummer, whereas on a deep silt loam soil (eg Templeton), irrigation can be extended out to every two weeks or more without yield loss.

Tip

Another way to calculate how much plant available water the soil holds is to use a neutron probe or Aquaflex to measure the SWC when the soil is at field capacity during winter, and again when the soil is dry and the crop is at permanent wilting point. A commercial irrigation monitoring service can also do this.

Table 4. The AWC to 1.0 m of a silt loam soil with different depths to gravel, and the necessary interval between irrigation events at different evapotranspiration (ET) rates assuming no stones in the upper layer

Depth to gravel (m)	AWC to 1.0 m depth (mm)	RAW from FC to TP (mm)	Days from FC to TP @ 3 mm ET/day	Days from FC to TP @ 5 mm ET/day	Days from FC to TP @ 7 mm ET/day
0.2	72	36	12	7	5
0.4	94	47	16	9	7
0.6	116	58	19	12	8
0.8	138	69	23	14	10
1.0	160	80	27	16	11

In some situations cultivation pans or compacted subsoils will stop root penetration. This reduces root depth to the depth of the impeded layer, so the presence of impeded soil layers must be known to accurately estimate crop root depth and AWC.

Maximum daily rate of water uptake

Supply of water to the crop is dependent on the available water capacity (AWC) of the soil and the rate that crop roots can extract it. A general rule is that a crop can extract a maximum of 10% of the AWC each day. So if a crop is growing in a soil with an AWC of 50 mm it will be able to extract a maximum of 5 mm/day of water. The following day there will be 45 mm of available water (assuming no rainfall or irrigation) and on this day the crop will be able to extract 4.5 mm of water. Therefore for the soil to meet water demand for optimum yield, AWC must be 10 times greater than daily ET. If we take the ET data for Lincoln (Figure 2), the AWC that must be present to meet crop demand ranges from 10 to 50 mm and peaks at 80 mm for days when ET is 8 mm/day. ET at Lincoln (which is representative of much of Canterbury) exceeds 6 mm/day on 5% of days. This means we should aim to ensure there is always at least 60 mm AWC in the soil and we can calculate appropriate trigger deficits from this.

Plants can only access 10% of the AWC in their root zone each day.

To calculate the AWC needed to avoid yield loss, multiply the ET x 10.

On light or shallow soils the potential yield may not be achievable because even when the soil is at field capacity, the AWC may be less than 10 x ET.

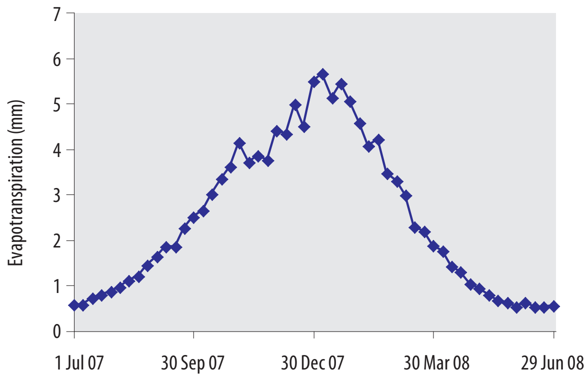

Figure 2. Average daily evapotranspiration rates (mm) for Lincoln.

Soil quality and its influence on available water capacity

One of the most important aspects of soil quality is its impact on soil AWC. In a soil with no layers that restrict root growth, the AWC is determined by the rooting depth of the crop. In Figure 3a, the AWC for deep rooting wheat is 200 mm growing in a deep silt loam soil but only 80 mm for shallow rooted potatoes.

The presence of limiting layers restricts rooting depth and alters AWC. In Figure 3b, a limiting layer of gravels has been introduced at 60 cm. The gravels have very low AWC and the impact on AWC at this depth has a greater effect on the deeper rooted crop (wheat AWC = 145 mm) than the shallow rooted crop (potato AWC = 75 mm). If gravels were shallower or there were stones in the upper soil layer, the AWC would be even less.

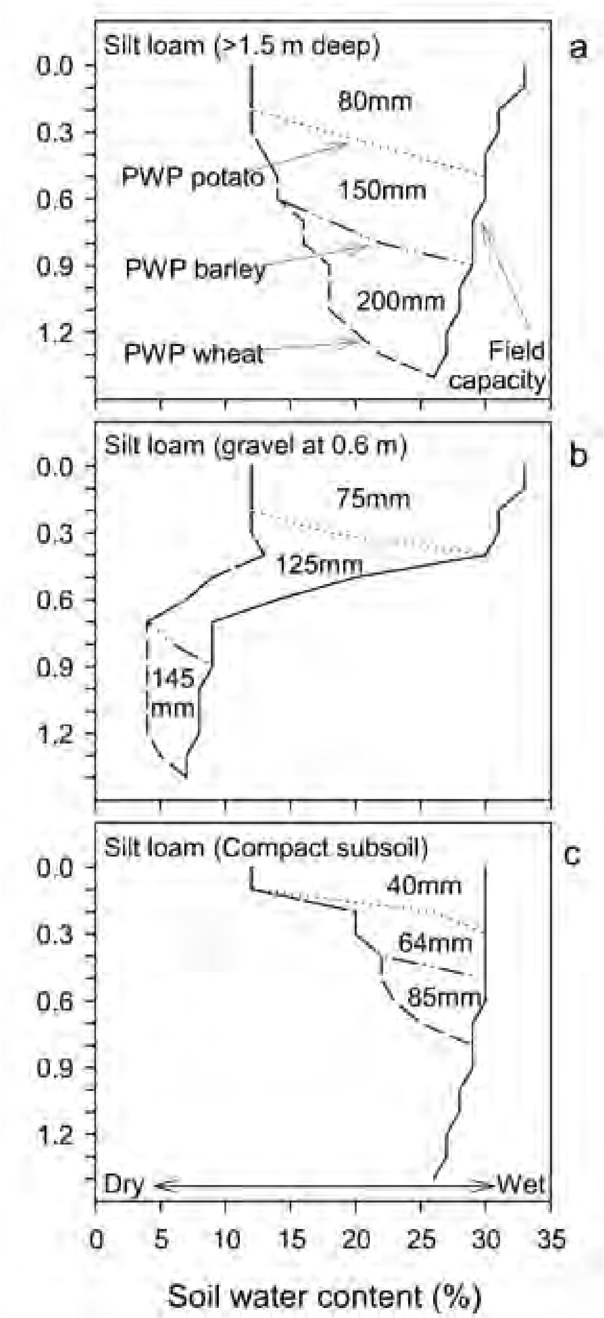

Figure 3. Field capacity and permanent wilting point (PWP) for a range of crop/soil combinations. Numbers above each of the PWP lines represent the available water capacity (AWC) for the three crops specified

Soil compaction is another example of a limiting layer and effects AWC in two important respects. Firstly, soil compaction reduces pore space between soil aggregates that are important for water storage. Secondly, compaction also reduces the ability of plant roots to explore the soil. In Figure 3c, a compacted sub soil at 30 cm has been introduced and AWC has been dramatically reduced for all crops. Potato crops in particular are very sensitive to compaction and it is common for them to only penetrate to 30 cm depth, and in this case, results in an AWC of only 40 mm. This crop will be highly prone to water stress and will not achieve maximum yield because some moisture stress is inevitable.

Soil management

Soils which have been direct drilled for a number of years differ from conventionally cultivated soils in terms of aggregate size, aggregate stability, porosity and organic matter. These factors influence soil AWC. Trials at the FAR Chertsey Arable Site and the Millennium Tillage Trial (MTT) at Lincoln show that these parameters are typically improved in the top soil as cultivation intensity is decreased. In the MTT, the soil structural condition score card (SCS) was used to evaluate the structural condition of soils in each of the tillage treatments. Scores ranged from 1 to 10, where 1 was poorest and 10 the best soil structural condition. After seven years of continuous cropping, both the minimum and no-tillage treatments maintained SCS well within the optimum range (5-10). However the SCS of intensive tillage soils fell below the previously established critical limit of 5 from 2005 onwards.

Cultivation also causes moisture loss from the soil (aeration, warming, residue burial) and reduced cultivation techniques help retain soil moisture, the key reason for adoption of direct drilling in dry environments such as Australia. Remedial cultivation such as ripping soils with a compacted layer may allow roots to access a greater volume of soil moisture.

Sources and further reading

McLaren, R.G. and Cameron, K.C. (1997) Soil Science: Sustainable production and environmental protection. Oxford University Press

White, J. and Hodgson, J. (2002) New Zealand Pasture and Crop science. Oxford University Press

4. Pulling these Factors Together

- Calculating trigger point for particular crop/paddock combination
- Prioritising crops
- Irrigator type

Calculating trigger point and refill amount for a particular crop/soil type combination

50% x AWC

By knowing a crop's rooting depth, and the type and depth of the various soil layers in the rooting zone, the AWC can be estimated for each crop/soil type combination as follows:

1. Estimate the root depth of the crop (RD in metres) considering time since planting and the possible presence of impeded layers. This can be estimated from sowing time (see section 3 and Table 1) or by digging a hole to find how far down roots have grown.
2. Calculate the AWC of each layer of soil within that root depth, adjusting non-gravel layers for stone content (see section 3 and Table 3).
3. Sum together the AWC of each layer within the root zone.

From the total AWC, the trigger point (TP) and refill amount (RA) for each paddock can then be calculated as:

- Trigger point (TP) = AWC x 0.5
- Refill amount (RA) = TP x 0.8

This calculation for refill amount will provide enough water to take the soil from trigger point to 90% of field capacity. This will ensure no drainage occurs from irrigation and there is some capacity in the soil to absorb any rainfall that may occur soon after irrigation.

Example calculation of AWC for a silt loam soil with gravel from 0.6 m and a crop with a rooting depth of 1.5 m

AWC silt loam = 160 x 0.6 = 96 mm

AWC gravels = 55 x 0.9 = 49.5 mm

AWC = 96 + 49.5 = 145.5 mm

TP = 145.5 x 0.5 = 72.7 mm

RA = 72.7 x 0.8 = 58 mm

Maximum daily rate of water uptake

On soils with a low AWC, the trigger point may need to be reduced when ET is high.

The previous section describes the commonly used rule for irrigation scheduling using a trigger deficit at 50% of AWC for a given crop/soil combination. This rule will ensure adequate irrigation practices for soil/crop combinations that have an AWC of 120 mm or greater because 50% of the AWC will leave at least 60 mm of available water in the soil. Because plants can only extract 10% of AWC per day, then 60 mm of soil water will provide enough moisture when ET is up to 6 mm/day (typical ET rates for summer). If ET exceeds 6 mm/day and/or the AWC is less than 120 mm, then water stress is likely. Thus the trigger point should be adjusted so there is always 60 mm of soil water remaining in the soil (Table 5).

Table 5. Calculating the trigger point for a range of soil AWC

Soil AWC (mm)	TP (mm) so 60 mm soil moisture remains in soil
40	Crop will be under water stress at ET>4 mm
80	20
120	60
160	100
200	140

Table 5 shows that for a soil with an AWC of only 40 mm, the crop will be water stressed when ET exceeds 4 mm/day even if the soil is at field capacity. Using data from the Lincoln weather station, ET would exceed 4 mm/day on approximately 25% of days in a typical season. Using the equations outlined in section 4, the refill amount is calculated as 16 mm, which would require frequent irrigation (every 4 days if ET were 4 mm/d). Many irrigation systems do not allow this frequency of irrigation so it is likely that supply will not meet demand at times during the season and yield will be less than the potential maximum. This helps explain why crop yields are always lower on very shallow soils (low AWC) even when they are fully irrigated.

Allowing for variability

To schedule irrigation optimally it is necessary to know the variability in soil physical properties across a paddock. For example, if irrigation is scheduled based on a heavier part of the paddock, the crop on lighter soil may not be irrigated adequately. In the past the water holding capacity of soil was measured by taking cores. These point measurements gave information for a specific location but not the whole paddock. Technology is now available to map soil water holding capacity over an entire paddock. An electromagnetic sensor dragged over a paddock measures soil electrical conductivity to a depth of about 1.5 m, which is closely related to soil texture and therefore water holding capacity. Maps generated from this data show the variability in soil physical properties across the area measured. In New Zealand there is currently one commercial service available for this mapping (http://www.gpsfarmmap.com/en/index.php). Crop yield maps can also indicate where soil types may be different.

Allowing for variability in the weather includes leaving around 20 mm soil moisture deficit after irrigation in case it rains (unless the AWC is very low as described in the previous section).

Prioritising crops

Which crop should take priority if there is insufficient water?

As the soil dries from the trigger point toward wilting point, potential yield decreases in a straight line (Figure 1). The slope of this line describes the relative yield decline (RYD). The bigger the potential yields, the greater the relative reductions in yield after TP. The rate of yield loss has been assessed for a range of crops and is described as a percentage of potential yield per mm of soil water deficit (SWD) above the TP (Table 6).

Table 6. Relative yield decline for a range of crops

Crop species	% decrease in potential yield for each mm below the trigger point
Maize*, oats, potatoes, sweetcorn	0.10%
Ryegrass seed	0.14%
Barley, peas and wheat	0.25%

**maize sensitivity to drought decreases with time because the TP increases as the root system develops*

The form of yield loss can change. For instance, early drought stress in barley reduces grain number mostly through the loss of tillers, whereas late drought stress results in small, pinched grain with high screening losses.

The yield response to irrigation is the result of avoiding a situation in which the trigger point is exceeded. In round terms, a 50 mm irrigation on a very healthy wheat crop (potential yield 13 t/ha) applied just before trigger point is reached is 13 t/ha x 50 mm x 0.25% = 1.63 t/ha. Assuming irrigation costs $100/ha ($2/mm) and the wheat is worth $300/t, the return would be $480/ha, a net gain of $380/ha.

For the same irrigation on a 2 t/ha ryegrass seed crop, the yield response would be 2 t/ha x 50 mm x 0.14% = 0.14 t/ha. At a value of $2,200/t, the return would be $308/ha, and return net to irrigation of $208/ha. In this example, if there was insufficient water it would pay to irrigate the wheat ahead of the ryegrass.

There is a spreadsheet on the FAR website where you can do this calculation for a range of crops. www.far.org.nz.

Tip

If the soil water content is below the trigger point and there are two warm summer days (equivalent to ET of 10 mm) there will be a potential yield loss of 1 to 3% depending on plant species.

Irrigator type

On soils with low AWC and hot dry weather with high ET, irrigation will be needed every few days. Centre pivot and linear move irrigators are ideal in this situation as the amount of water applied can be easily controlled, low rates can be applied and return times can be short.

5. Tools for Monitoring Soil Moisture

- Soil water budget
- Soil moisture meters

There are two main methods for scheduling irrigation: the soil water budget and soil moisture meters.

Soil water budget

So far we have covered how soil and crop factors will influence available water capacity, trigger point and refill amount. This information can then be used for irrigation scheduling. The most effective irrigation scheduling will measure or calculate soil water content (SWC) each day to determine when SWC will reach the trigger point. Irrigation will then be applied on this day at the refill amount. This practice will keep the SWC above trigger point so yield is maximised but maintain SWC below field capacity to minimise the risk of drainage and subsequent leaching.

Clearly the AWC of a paddock will change as root depth increases. Autumn sown crops will have roots close to the maximum depth by the time the irrigation season starts in the spring so there is no need to consider changing root depth for such crops. However, later spring and summer sown crops will still be extending their roots during the irrigation season so TP and RA will increase as the season progresses. Such crops may need irrigating more frequently and in smaller amounts earlier in their growth cycle to ensure they are not water stressed. A detailed irrigation schedule should take this into account.

Forecasting soil water content (SWC) using a water budget is based on the following equation:
SWC tomorrow = SWC today + irrigation + rainfall - evapotranspiration - drainage

ET gives a good estimate of transpiration when the crop is well watered and fully covering the ground. When the crop has incomplete ground cover a simple correction is achieved by halving ET if crop cover is less than 50% and using the full rate of ET if crop cover is greater than 50%. Evaporation is more difficult to estimate as it changes substantially depending on time since a wetting event. A general rule is that for a crop with 50% ground cover, evaporation will be 50% of ET following a wetting event, then decrease to 35% on day 2, 20% on day 3 and then be 15% on all following days. Crop calculators are more accurate. They predict transpiration and evaporation from detailed calculations considering ground cover and soil water content.

If the SWC is above the TP, the effective crop ET will be equal to ET. When SWC is below the TP, effective crop ET will be the lesser of ET (demand) or soil water supply. Soil water supply is the amount of water that the crop can extract from the soil each day and is well represented as 10% of the available water in the soil. For example, if the available water content is 20 mm, soil water supply will be 2 mm on that day (see Section 3. Maximum daily rate of water uptake).

Rainfall and irrigation need to be recorded for the water budget to be accurate. Rainfall varies substantially over short distances so it is best to use records from a rain-gauge on the farm. The amount of irrigation applied may vary from the manufacturer's specifications. It is a good idea to check the actual depth of water applied. There are also a number of inefficiencies associated with irrigation systems and these may need to be accounted for in a water budget. There are commercial services available to assess the application rates and efficiencies of irrigators and provide advice on possible improvements. There are some easy checks growers can do themselves (see Section 6. Distribution uniformity). In the absence of such an assessment it can be assumed that an irrigator is 80% efficient, so the application amount determined from rain-gauges or flow meters should be multiplied by 0.8 for entry into the water budget.

Drainage should be minimal under well managed irrigation because SWC will be maintained below field capacity. However, drainage can still occur when rainfall events fill the soil to above field capacity. While drainage is included in the soil water budget, the need to calculate it can be avoided by assuming that SWC can not exceed field capacity.

For autumn sown crops (where irrigation is usually not needed in the autumn) it is appropriate to assume the SWC will be at field capacity on 1 July and start the water budget from there. For spring and summer sown crops start the water budget on the day of planting. In this case, it will be necessary to make an assumption about SWC on the day of planting. If the soil is wet, SWC could be assumed to be at field capacity, if it is moderate, assume 80% of field capacity and if it is dry, assume 60%.

Example of a soil water budget
An example of a soil water budget is presented in Figure 4. A wheat crop was planted on 1 August. The soil has 0.6 m of silt loam overlying gravels and a root depth of 1.0 m giving an AWC of 120 mm, a TP of 60 mm, and a refill amount of 50 mm.

- SWC remains close to field capacity during July and August while ET is low and a number of large rainfall events occur.
- SWC begins to drop in September when ET increases and rainfall is low.
- SWC reaches the TP for the first time in early October and 50 mm of irrigation is applied. This shows up as 40 mm in the water budget because of the irrigation efficiency of 80% and returns the SWC to 100 mm.
- A second irrigation is triggered in late October, followed soon after by a rainfall event. Because the refill amount allows some capacity to absorb rainfall in the soil this does not cause any drainage.
- Irrigation is frequent through November as ET is high and rainfall is low. Substantial rainfall in December means irrigation is not needed again until January.
- This crop was expected to finish grain fill at the end of January and irrigation is withheld in late January, aiming to have SWC at trigger point soon after grain filling finishes and the crop is no longer sensitive to moisture stress.

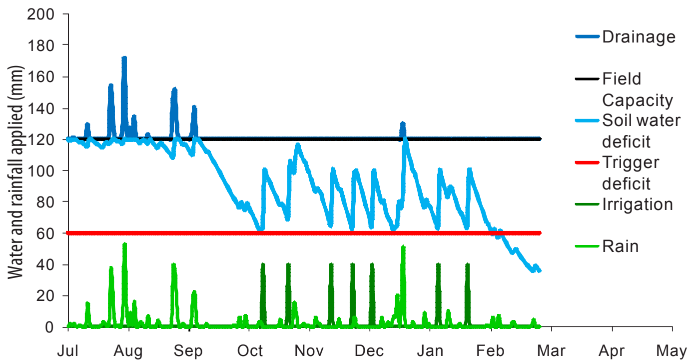

Figure 4: An example of a soil water budget

To apply such a soil water budget throughout the season it is necessary to enter actual ET, rainfall and irrigation information up to the current date to calculate the current SWC. To predict when the next irrigation is needed (when future SWC reaches trigger deficit) it is also necessary to have an estimation of the upcoming weather events. Upcoming ET can be represented by long-term average values for the area and, for the purpose of irrigation scheduling, assume upcoming rainfall is zero. If ET substantially differs from long term averages, or if rainfall occurs between the current date and the next scheduled irrigation date, it may be necessary to update the water budget to determine if irrigation is needed sooner (in hot conditions) or later (if rainfall occurs) than the initial date.

When to stop irrigating

The scenario outlined above assumes that crops require optimal water supply at all times. Some crops benefit from a period of moisture stress when irrigation should not be applied (e.g. white clover seed crops). To calculate when irrigation should be stopped to produce a stress period, identify when the period of stress is wanted. Use the water budget to work out when irrigation should be stopped to ensure the SWC will be below TP at that time. The water budget can be used in a similar manner to determine when irrigation should be stopped at the end of the season. Estimate when the crop will complete grain fill, identify this point on the water budget and stop applying irrigation so SWC is reaching TP at about this time. The wheat calculator forecasts the date grain fill is complete.

AquaTRAC™ (irrigation scheduling software) is available from FAR, it includes:

- Multi-paddocks
- Imported weather data
- The ability to input actual soil moisture measurements
- Date of next scheduled irrigation
- Prioritises which crops to irrigate if water is limited

Soil Water Measurement

A soil water budget is inexpensive and reasonably accurate if it is done carefully. However, errors can accumulate over time so soil moisture measurements are a good way of getting the budget back on track. There are a range of devices that can be used including:

- Spade (grower judgement)
- Tensiometer
- Gypsum block
- Aquaflex cables
- Neutron probe
- Capacitance meters
- Time domain reflectometry

Most soil moisture meters need interpretation for effective irrigation scheduling. None of these devices measure soil water content in mm, rather some measure of soil wetness; either the soil water content as a % or the soil water potential.

- Soil water content is a measure of the percentage volume water present in the soil. However a measure of the soil water content does not tell you how much of that water is available to the plant. Knowledge of the soil and crop must still be used to determine the TP.
- Soil water potential is a measure of how tightly the soil holds water and consequently how available the water is to the plant. Soil water potential indicates how freely water is available to the plant and therefore when the trigger point is reached, but not how much RAW is stored in the soil. This could be calculated by recording the ET or mm of water used from FC to the TP.

Measurements from neutron probes are easily converted to mm of soil water. Measurements from other devices are more difficult to interpret because the translation from the units they measure to actual amounts of available water in the crop's root zone are greatly influenced by soil texture, the presence of stones, the method of installation, the time since installation, the position of installation (relative to soil variability within the rest of the paddock) and the depth of installation (relative to the crop's root depth). All of these things must be taken into account in determining when soil water measurements mean irrigation is required or not.

Soil Moisture Meters

Tensiometer

Tensiometers have a porous cup at their base, an interconnecting plastic tube full of water and a vacuum gauge at the top. The device is inserted into the soil making sure there is good contact between the porous cup and the soil. Tensiometers measure soil water potential. As the soil dries, water is sucked from the tube into the soil causing a suction gradient which is detected by the gauge. If the soil is wet then the soil has a greater water pressure than that of the plastic tube which causes water to passively diffuse into the cup. Consequently the vacuum in the plastic tube is decreased.

If one tensiometer is placed in the middle of the active roots it can be used for deciding when to turn the irrigation on. A tensiometer placed toward the bottom of the active roots can be used to gauge when the root zone is full. Care must be taken when shifting the tensiometer that the gauge is not bumped, therefore losing its accuracy.

Positive attributes:

- It is relatively cheap.
- Measures soil water potential which is more relevant to plant stress and easy to interpret.

Negative attributes:

- Data needs to be manually collected.
- Operating range does not extend as well to dry soils.

Gypsum Block

The gypsum block also measures soil water potential. As the soil dries the soil water potential decreases and the plant needs to exert more energy to access that water. The reading from the meter gives directly whether the crop has adequate soil moisture to maximise yield. In comparison meters that measure soil moisture content need interpretation.

The Gypsum block is composed of a porous block (the gypsum) which contains two electrodes. The porous structure of the block allows water movement in and out with the immediate soil environment. The water in the soil will reach an equilibrium with the water in the gypsum block and the electrical resistance is then determined and related to soil water potential.

Positive attributes:

- It is relatively cheap.
- Measure soil water potential which is more relevant to plant stress and easy to interpret.
- A logging system is available and the soil moisture trend over time can be displayed.

Negative attributes:

- Not that accurate in wetter soils.
- Blocks dissolve over time.

Aquaflex

Aquaflex uses time delay transmission (TDT) technology to measure soil water content and soil temperature. The sensor consists of a 3 m long, dual-core wire with a flexible plastic coating. An electrical pulse is sent along the strip. The electric current changes shape and speed according to the amount of moisture present. The tape is buried in a trench. It can be placed on an angle down through the root zone. Another tape could be placed at the base of the root zone to detect if over watering is occurring.

It does require some work to install compared with soil moisture probes. Soil disturbance can cause unrepresentative conditions so the cable should be installed early to allow time for the soil to settle around the tape.

Positive attributes:

- Allows for continuous monitoring so that the change in soil moisture and temperature over time can be captured.
- Data can be downloaded directly onto a laptop computer or transmitted to a computer.
- Measuring soil water content across a larger volume gives a more representative reading than probe type sensors.

Negative attributes:

- Relatively expensive.
- Soil disturbance during installation.
- Need to remove before cultivation.

Figure 5. Installing aquaflex

Neutron probe

The neutron probe measures soil water content from sequential depths. It is a robust piece of equipment used for research and commercial irrigation scheduling services.

It consists of a nuclear source/detector suspended from a cable and a housing which contains the count/storage electronics. Aluminium access tubes are installed at the site.

The source/detector is lowered down the tube to the required depth and a reading taken.

The neutron probe contains a small amount of radioactive material which when activated, releases a known number of fast neutrons. The technique is based on measurement of fast moving neutrons that are slowed by collision with hydrogen in the soil. The neutron probe can then calculate the amount of hydrogen present in the immediate soil. It is mainly the hydrogen atoms contained in water molecules which are responsible for slowing the neutrons and therefore, the measurement can be related to the amount of soil water.

Positive attributes:

- The most robust, accurate method of soil water content measurement.
- Measures a large volume of soil.
- Not affected by access tube air gaps.

Negative attributes:

- Expensive to purchase.
- Owner requires a licence.
- Needs to be calibrated to specific soil type.
- Manual reading.

Figure 6. Neutron probe

Capacitance meters

These are either buried sensors, usually connected to a datalogger (e.g. Enviroscan), or more portable methods with access tubes (e.g. Gopher), or steel spikes (e.g. Thetaprobe). These devices measure soil water content. Their high sensitivity, lack of robustness and calibration problems have limited their use in the field to date.

Here the Environscan is discussed in more detail. This device has a number of capacitance sensors installed at different depths in a PVC access tube. This allows the grower to see where moisture is being lost from the soil profile. The EnviroSCAN takes readings as frequently as every minute.

Positive attributes:

- Continuous recording.
- Can display trends in soil water on the computer screen.
- Infiltration rate, root activity and crop water use may be inferred.
- Can monitor multi depths at once.

Negative attributes:

- Relatively expensive.
- Not portable.
- Measurement very sensitive to good access tube installation which is difficult on stony soils.

Time Domain Reflectometry (TDR)

The TDR method involves connecting a small electronic device to a pair of metal rods which are inserted into the soil. The rods are usually about 5 mm in diameter and normally no longer than 70 cm. Good contact with the soil is critical. The electronic device emits a pulse of electromagnetic radiation, similar to a radar pulse which travels down the rods. The TDR device then measures the time taken for the pulse to be reflected back from the end of the rods and this is related to the soil water content. Used in research, especially for close-to-surface soil measurements.

Positive attributes:

- Can easily do manual readings at multiple sites.
- Good accuracy.
- Large measurement volume.

Negative attributes:

- Need different length rods to get measurements for different depths.

Sources and further reading

McLaren, R.G. and Cameron K.C. (1997) Soil Science: Sustainable production and environmental protection. Oxford University Press.

Charlesworth, P. (2005) Irrigation insights No.1. Soil water monitoring: An information package. Land and Water Australia.

6. Improving Water Use on Farms

- Matching crop demand to water supply
- Irrigator management

Matching crop demand to water supply (sowing time/crop rotation)

Generally when ET is high in summer it is difficult for irrigation systems to keep up with crop demand. Arable growers can manage this situation by including crops that don't all require full irrigation during this period. For example, white clover requires less water up to and during flowering and pasture in the rotation may be sacrificed to fully irrigate more valuable crops.

For unirrigated, or inadequately irrigated crops, earlier sowing will reduce the risk of yield loss from water stress. This is because the crop's roots can grow deeper and maximise the use of the soil water. Also, the crop will be through more of its growth cycle before the high ET rates of summer reduces SWC and causes water stress.

Irrigator management

i. Sources of loss

We can use our knowledge of crops, soils and soil water to determine when to irrigate and how much. The final part of the package is to ensure the irrigator is applying the right amount of water and that none of the water being applied is lost.

There are many pathways for water loss in an irrigation sytem. Many people think the most water loss is caused by strong winds or daytime watering. In reality, the main water loss is from poor distribution uniformity (Table 7). Distribution uniformity (DU) describes how evenly the irrigator applies water to the paddock. A system will never reach 100% uniformity and will create regions of under and over irrigation.

Table 7. Type and amount of water loss from irrigation systems.

Loss component	Range	Typical
Leaking pipes	0-10%	0-1%
Evaporation in the air	0-10%	<3%
Wind blowing water off target (drift)	0-20%	<5%
Interception (canopy losses)	0-10%	<5%
Surface runoff (spray irrigation)	0-10%	<2%
Uneven application and/or excessive application depths and rates	5 - 80%	5 - 30%

ii. Distribution uniformity (DU)

A system with a low DU means that a paddock is being watered less uniformly (evenly) than a system with a high DU. Different types of irrigators have different inherent DUs, with centre pivots and lateral moves having a design efficiency of around 80 - 90% and rotating booms around 60 - 70%. Examples of irrigator uniformities found in a recent survey are given in Table 8, these show that the extra amount of water needed to ensure that the whole paddock receives the desired amount of water ranges from 17% to 122% more than what was actually applied.

Table 8. Water applications and distribution uniformities measured on six irrigation systems, together with the amount of water which would need to be applied to cover whole paddocks with the intended amount.

System type	Amount applied (mm)	DU %	Minimum amount to water whole paddock with applied amount (mm)	% extra water	Extra cost ($/ha/ irrigation)*
Centre pivot	9	85	10.6	18	3
Centre pivot	11.6	67	17.3	49	11
Lateral move	23	84	27	17	8
Rotorainer	50	70	71	42	42
Rotorainer	34	57	60	76	52
Gun	50	45	111	122	122

**Assuming irrigation costs of $2/mm/ha*

DU is relatively easily checked and all it needs is at least 20 plastic buckets and a reasonably accurate liquid measuring device. For centre pivot and lateral move irrigators, the buckets are laid out evenly across the line of travel, and the irrigator is run over them. For travelling gun and boom irrigators the buckets are left in place while the adjacent runs are irrigated to account for overlapping irrigation. The amount in each bucket is measured and converted to mm of water by dividing the water volume by the area of bucket.

DU (%) is the total amount in the 25% of buckets containing the least amount of water, divided by the total amount in all the buckets.

The irrigation rate (mm/hr) is calculated from the average depth of water from all the buckets divided by the time taken for the irrigator to pass over the buckets.

Guidelines and calculation sheets designed for growers to do their own assessment are available at www.pagebloomer.co.nz/resources/tools/irrigation-calibration.

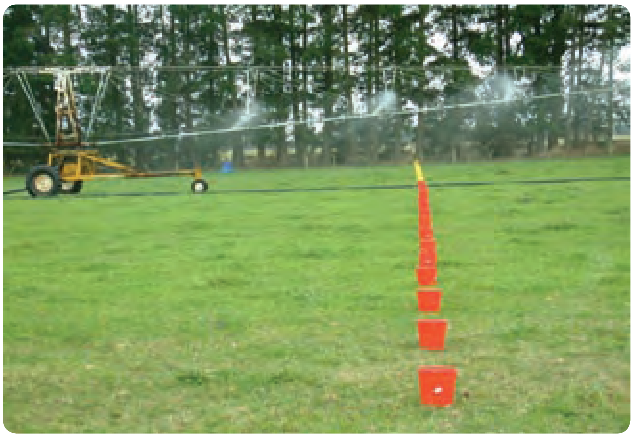

Figure 7. Measuring distribution uniformity of a travelling boom irrigator

To ensure complete coverage of a paddock with a planned amount of water means that you have to apply the planned amount (say, 50 mm of irrigation) divided by the uniformity. So if the DU is 50%, the planned application of 50 mm is divided by 0.5. This tells the farmer that some areas of the paddock would actually only receive 25 mm of the planned 50 mm, which means that the farmer would need to double the planned application amount to ensure that enough water is applied to those areas that get the lowest amount. However doubling the application amount is not desirable, since the well-watered parts of the paddock would then get far too much water (in this case, up to 100 mm), leading to drainage and runoff. To minimise the risk of water loss, ensure that your system is performing to its maximum uniformity. This will also improve overall crop production and minimise your water use (and costs!). It will also minimise risks of nutrient leaching which has a financial cost and environmental impact.

Common causes of low DU are related to poor irrigation set-up and/or maintenance such as mismatched pump pressure delivery and irrigation pressure requirement, poorly set variable speed drives, blocked lines and sprinklers, and poorly matched sprinklers fitted along the irrigator arm. Sprinklers are active components of your irrigation system and suffer wear and tear resulting in losses in DU. Most of the simpler problems are easily fixed. Having the performance of your irrigator evaluated by qualified consultants will point out any sources of reduced performance, and rectifying the problems will soon save you the costs of the evaluation.

Even with a well set-up and maintained irrigation system, significant losses can occur through poor irrigation management, which includes over and under-watering, irrigating too early or too late, and application rate exceeding soil infiltration rate. Applying more water than the existing deficit will result in more water being applied than the soil can hold, therefore the excess will be lost through drainage and runoff. This wastes water through drainage and increases pumping costs, for no additional crop growth.

Improving the DU by 5% results in savings of water of 19 mm and cost savings of $38/ha at $2/mm assuming applying 300 mm. If applying 300 mm in an average irrigation season with an irrigator covering 100ha a 5% saving equates to $3800 or the ability to irrigate a further 5ha/year. Using the example for wheat on page 13 at $380/ha net = $1900 net on top of the savings.

When installing a new irrigation system it is essential to specify the DU the system has to meet in the supply contract. A good DU for a centre pivot or lateral move irrigator is 85 to 90.

Sources and Further reading

Martin, R.J., Thomas, S.M., Zyskowski, R.F., and Stevens, D.R. Irrigation efficiencies. Provided by SIDE - South Island Dairy Event, New Zealand.

Costs

Applying water to crops will not always provide an economic return to growers and the decision to install an irrigation system or to irrigate a crop should only be made with good knowledge of the costs, and potential returns from irrigation.

In this FAR Focus a water cost of $2/mm applied has been used (based on a study of five irrigated arable farms). This cost is made up of operating costs - pumping, labour, R&M and supply charges and ownership costs including depreciation, insurance and interest.

Growers can reduce the costs of irrigation by improving DU, installing energy efficient pumping systems and applying the water to meet crop demand.

In this FAR Focus irrigating did not increase yields in barley in all years. Similarly in FAR Arable Extra 90 Cost of Prodution the gross margin for irrigated crops was not always better than dryland crops.

7. Glossary and Acknowledgements

Glossary

Available water capacity (AWC)
The amount of water a soil can store for plant growth. Also called plant available water (PAW).

Distribution uniformity (DU)
Distribution uniformity describes how evenly an irrigator applies water to a paddock.

Evapotranspiration (ET)
The rate a plant uses water for transpiration plus evaporation from the soil surface.

Field capacity (FC)
After rapid drainage has ceased and the soil water content has become relatively stable. Also called the drained upper limit.

Permanent wilting point (PWP)
Amount of water in the soil at which plants are permanently wilted. Also called the lower limit.

Plant available water (PAW)
The amount of water a soil can store for plant growth.

Refill amount (RA)
80% of trigger point.

Readily available water (RAW)
The amount of water between field capacity and trigger point.

Relative yield decline (RYD)
As the soil dries from the trigger point toward wilting point potential yield decreases in a straight line.

Rooting depth (RD)

Soil water content (SWC)
The volume of water in the soil.

Soil water deficit (SWD)
The difference between the amount of water in the soil at any time and the amount at field capacity.

Soil water potential (SWP)
A measure of how tight the soil holds water and therefore the degree of difficulty a plant will have in removing water.

Trigger point (TP)
The point where plants can no longer extract enough water for maximum growth. Also called the critical deficit, stress point or refill point.

Acknowledgements

Funders
FAR would like to acknowledge funding support from the MAF Sustainable Farming Fund (MAF SFF) and Horticulture NZ for this publication

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FAR Focus
ISSN 1175-5504

Irrigation Management for Cropping
A Growers Guide
ISBN 978-0-9864533-4-2

ADDING VALUE TO THE BUSINESS OF ARABLE FARMING