Training Course

Irrigation #1

March 2025

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Learning processes

- Water use, evapotranspiration rates, crop coefficients
- Soil water supply (texture, varietal rooting depth, compaction)
- Definitions of soil moisture deficits (critical, limiting, allowable, scab)
- Scheduling methods and practice
- Benefits/disadvantages of soil moisture measurement tools
- Application technology (equipment selection, operation, uniformity)
- Effect of irrigation on crop quality

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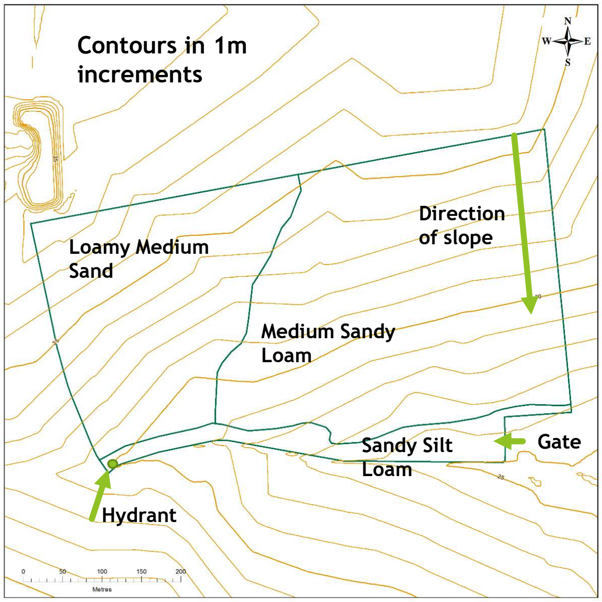
Scenario: how would you plan irrigation in this field?



Additional site information

Crop
Early maincrop potatoes for storage market
Previous crop
Wheat which was established late after the previous sugar beet crop
Topsoil depth
Mostly 300-350mm
Sub-soil
Mostly Loamy Coarse Sand
Pressure at Hydrant
8.5 bars

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In order to use irrigation more efficiently, growers must:

- Understand crop demand for water
- Maximise the quantity and rate of water extraction from the soil
- Utilize as much rainfall during the growing season as possible and avoid drainage
- Maximise tuber quality (common and powdery scab, lenticel eruption, processing quality, shape and internal defects)
- Minimise losses from irrigation, particularly during early season when SMDs are small (e.g. scab control)

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Penman-Monteith ET

$$\lambda_v E = \overbrace{\frac{\Delta(R_n - G) + \rho_a c_p (\delta e)\, g_a}{\Delta + \gamma\,(1 + g_a/g_s)}}^{\text{Energy flux rate}} \quad \Longleftrightarrow \quad ET_o = \overbrace{\frac{\Delta(R_n - G) + \rho_a c_p (\delta e)\, g_a}{(\Delta + \gamma\,(1 + g_a/g_s))\, L_v}}^{\text{Volume flux rate}}$$

λ_v = Latent heat of vaporisation. Energy required per unit mass of water vaporised. ($J\ g^{-1}$)
L_v = Volumetric latent heat of vaporisation. Energy required per water volume vaporised. (L_v = 2453 $MJ\ m^{-3}$)
E = Mass water evapotranspiration rate ($g\ s^{-1}\ m^{-2}$)
ET_o = Water volume evapotranspired ($mm\ s^{-1}$)
Δ = Rate of change of saturation specific humidity with air temperature. ($Pa\ K^{-1}$)
R_n = Net irradiance ($W\ m^{-2}$), the external source of energy flux
G = Ground heat flux ($W\ m^{-2}$), usually difficult to measure
c_p = Specific heat capacity of air ($J\ kg^{-1}\ K^{-1}$)
ρ_a = dry air density ($kg\ m^{-3}$)
δe = vapour pressure deficit, or specific humidity (Pa)
g_a = Conductivity of air, atmospheric conductance ($m\ s^{-1}$)
g_s = Conductivity of stoma, ($m\ s^{-1}$)
γ = Psychrometric constant ($\gamma \approx 66\ Pa\ K^{-1}$)
(Monteith, 1965):[4]
Note: Often resistances are used rather than conductivities.

$$g_a = \frac{1}{r_a} \quad \& \quad g_s = \frac{1}{r_s} = \frac{1}{r_c}$$

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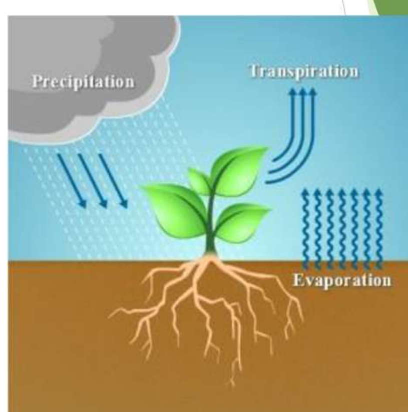
Requirements for Penman-Monteith ETo

- Energy (radiation, sunshine hours + latitude)
- Air temperature (max, min, mean)
- Relative humidity (max, min, mean)
- Windspeed (km/h or km/day)



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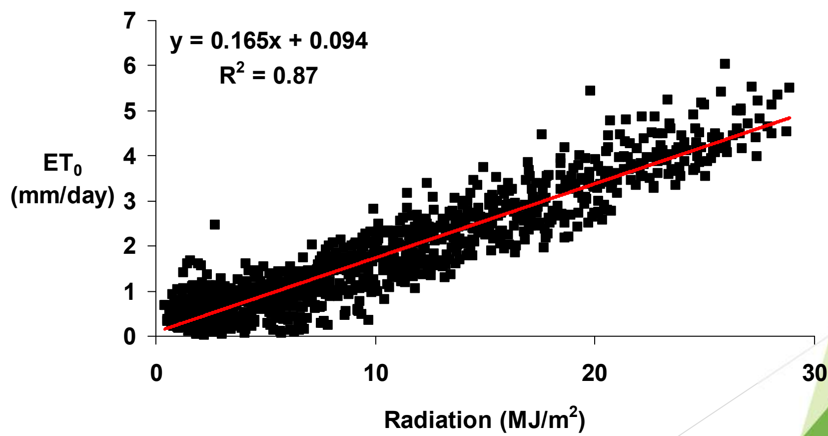
Basics: incident radiation (energy) drives evapotranspiration (and yield)



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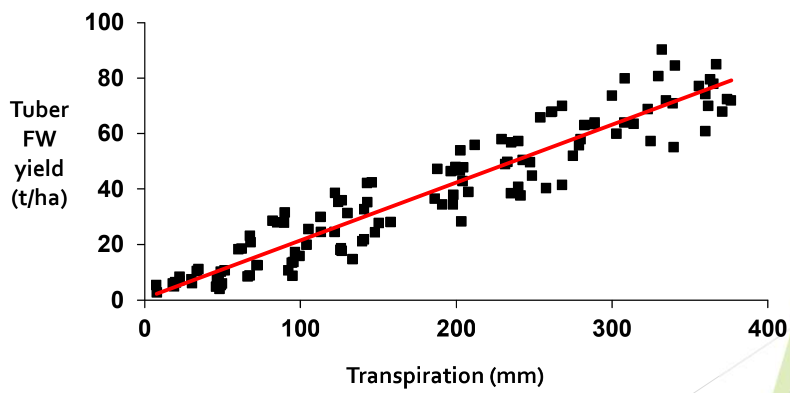
There is a close relationship between yield and transpiration



Source: Stalham (1989)

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Water use efficiency

- 0.24 t/ha/mm of water USED by the plant (= 6 t/ha per 25 mm)
- This is NOT the same as irrigation response, which ranges from -1.5 to 5.6 t/ha/25 mm APPLIED

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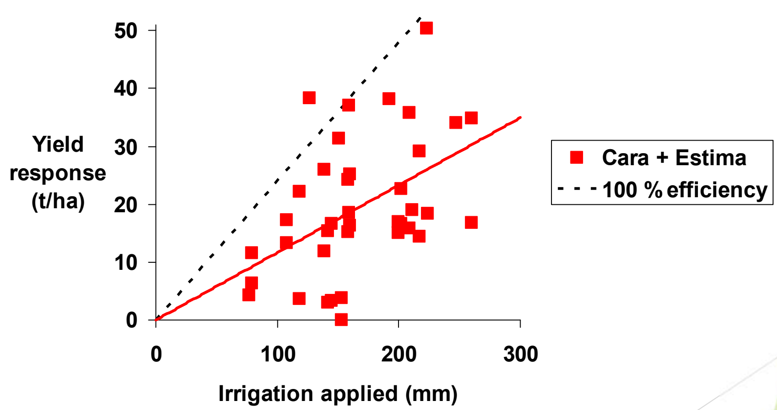
Is a **big** improvement possible in irrigation use efficiency?



Source: CUF Reference Crop 1990-2010

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Why are potatoes drought sensitive?

- Low below-ground conductance
  - Limited rooting
    - Best examples: 20 km/m^2, which equals typical winter cereals and sugar beet
    - Typically 8-10 km/m^2
    - Frequently 3-4 km/m^2 in compacted soil
  - Poor ability to transport water within plant (narrow root and xylem diameter)

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Why do varieties differ in drought resistance?

- Rooting characteristics
  - Rate of growth
  - Depth
  - Density
  - Time and rate of senescence
- Leaf/canopy characteristics
  - Ground cover longevity
  - Stomatal conductance
  - Leaf vs tuber water potential
  - Tolerance of high temperatures

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Varietal differences in rooting: longevity of root growth not rate

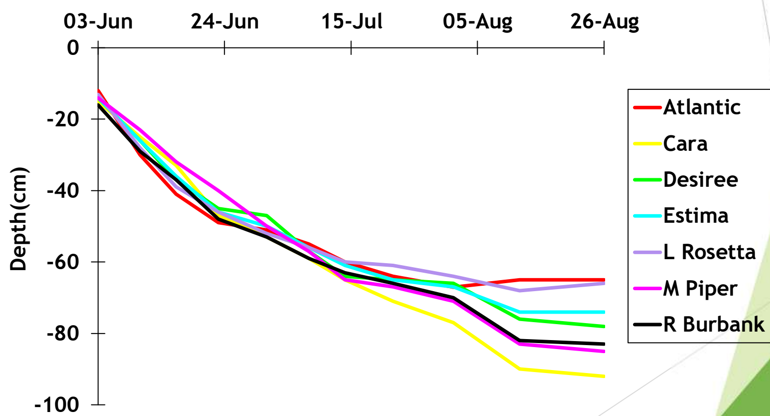

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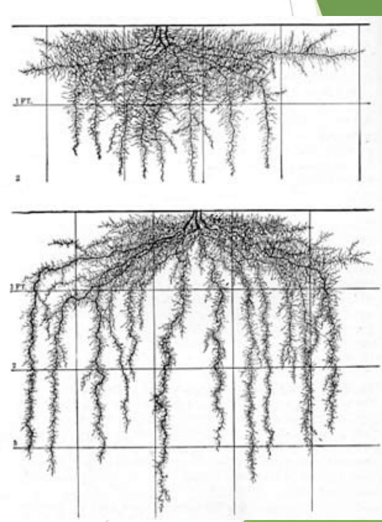
FIG. 3.—One end of the first trench used for the study of root systems. Pullman, Washington, 1934.

1930s



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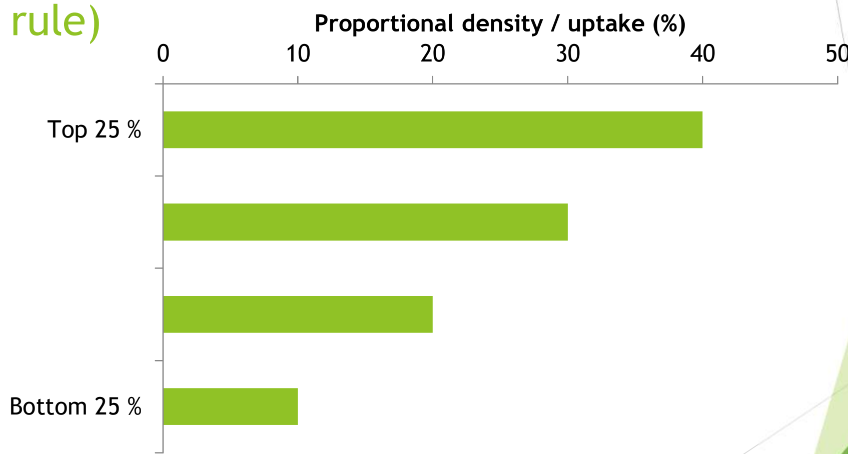
Changes in rooting density and water uptake with depth (40 : 30 : 20 : 10 rule)



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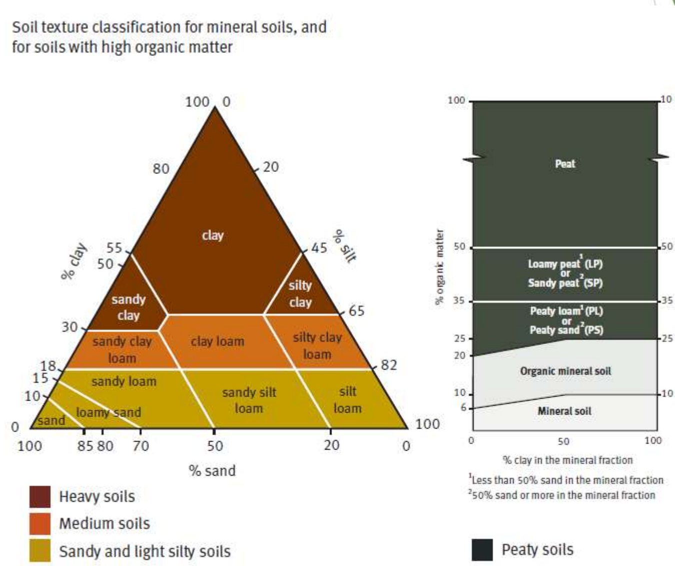
Soil texture



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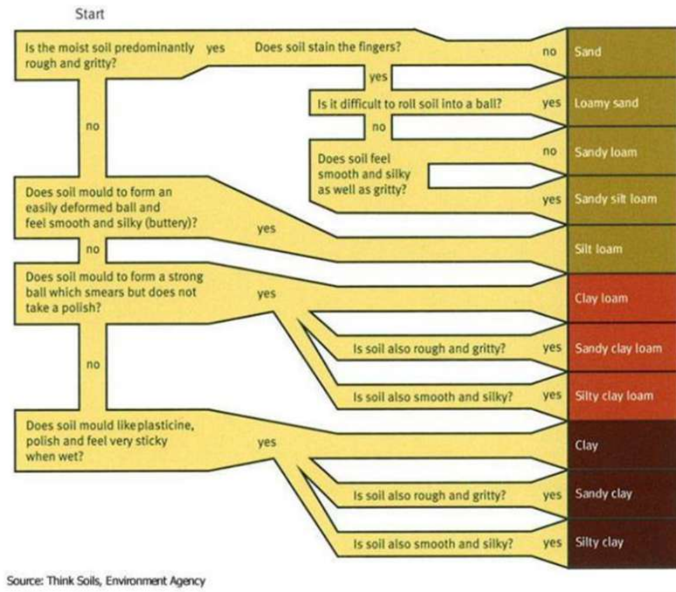
Soil texture



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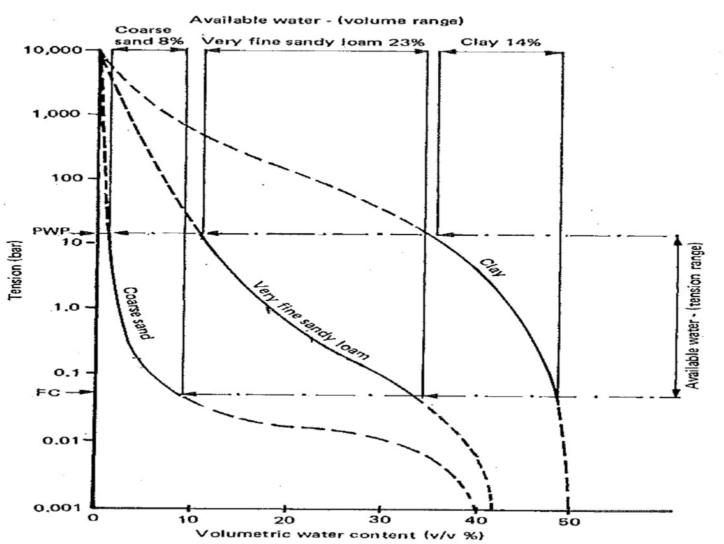
Water release



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Easily Available Water Holding Capacity

Soil AWHC FC-60kPa

						Stone content (%)					
Texture	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
cS	0.29	0.29	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.25	0.25
mS	0.57	0.55	0.53	0.51	0.50	0.48	0.46	0.44	0.42	0.40	0.39
fS	0.68	0.66	0.63	0.61	0.58	0.56	0.54	0.51	0.49	0.46	0.44
LcS	0.64	0.62	0.60	0.57	0.55	0.53	0.51	0.49	0.46	0.44	0.42
LmS	0.70	0.68	0.65	0.63	0.60	0.58	0.55	0.53	0.50	0.48	0.45
LfS	0.75	0.72	0.70	0.67	0.64	0.61	0.59	0.56	0.53	0.50	0.48
cSL	0.72	0.69	0.67	0.64	0.62	0.59	0.56	0.54	0.51	0.49	0.46
mSL	0.78	0.75	0.72	0.69	0.66	0.64	0.61	0.58	0.55	0.52	0.49
fSL	0.84	0.81	0.78	0.74	0.71	0.68	0.65	0.62	0.58	0.55	0.52
vfSL	0.90	0.87	0.83	0.80	0.76	0.73	0.69	0.66	0.62	0.59	0.55
cSZL	0.75	0.72	0.70	0.67	0.64	0.61	0.59	0.56	0.53	0.50	0.48
mSZL	0.84	0.81	0.78	0.74	0.71	0.68	0.65	0.62	0.58	0.55	0.52
fSZL	0.87	0.84	0.80	0.77	0.74	0.70	0.67	0.64	0.60	0.57	0.54
ZL	0.95	0.91	0.88	0.84	0.80	0.76	0.73	0.69	0.65	0.61	0.58
ZCL	0.82	0.79	0.76	0.73	0.70	0.67	0.63	0.60	0.57	0.54	0.51
CL	0.84	0.81	0.78	0.74	0.71	0.68	0.65	0.62	0.58	0.55	0.52
SCL	0.87	0.84	0.80	0.77	0.74	0.70	0.67	0.64	0.60	0.57	0.54
SC	0.80	0.77	0.74	0.71	0.68	0.65	0.62	0.59	0.56	0.53	0.50
ZC	0.87	0.84	0.80	0.77	0.74	0.70	0.67	0.64	0.60	0.57	0.54
C	0.84	0.81	0.78	0.74	0.71	0.68	0.65	0.62	0.58	0.55	0.52
Z	1.00	0.96	0.92	0.88	0.84	0.80	0.76	0.72	0.68	0.64	0.60
P	1.11	1.06	1.02	0.97	0.93	0.88	0.84	0.79	0.75	0.70	0.66
PLS	0.91	0.87	0.83	0.80	0.76	0.73	0.69	0.66	0.62	0.59	0.55
PSL	0.95	0.91	0.87	0.83	0.80	0.76	0.72	0.68	0.65	0.61	0.57
PCL	0.98	0.94	0.90	0.86	0.82	0.78	0.74	0.70	0.67	0.63	0.59
PZCL	0.97	0.93	0.89	0.85	0.81	0.77	0.74	0.70	0.66	0.62	0.58
PC	0.98	0.94	0.90	0.86	0.82	0.78	0.74	0.70	0.67	0.63	0.59
Chalk	0.30	0.30	0.29	0.29	0.28	0.28	0.27	0.27	0.26	0.26	0.25

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Bucket and contents analogy

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But the buckets can be full of… sand, sandy loam, silt loam, peat etc.

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Water holding capacity to 75 cm (typical max. bucket capacity)

Soil texture	Easily AWHC (mm)	Difference from mS
mS	33.3	0
LmS	42.8	9.5
mSL / mSZL	47.5	14.2
fSZL / ZL	54.8	21.5
C / CL	49.0	15.7

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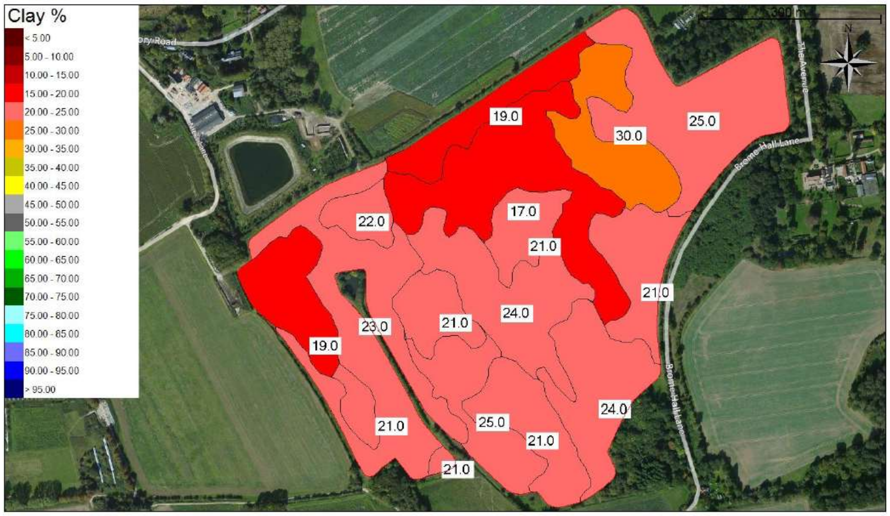
Field Maps (Half)

Main Business: Agrii SoilQuest
Year: 2013
From: 01/01/2013 To: 07/03/2013

Agrii
Tel 07889 413190
stuart.alexander@agrii.co.uk

SoilQuest

2013 Park		Variety: Unallocated	Crop: Unallocated		Working ha: 39.68
Nutrient	Type	Date	Index Ref	Index Num	mg/L or SNS kg/ha
Clay %	Soil Nutrients	07/03/2013		22.13	0.00



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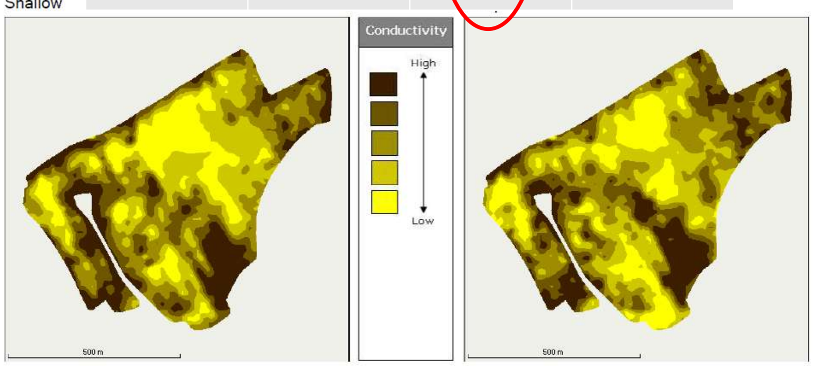
Precision agronomy service from Agrii

Results
Scan Da
Farm:
Field:
Shallow

Clay content (%)	Easily AWHC (% vol.)	Limit SMD (mm)	% of field
16-20	7.8	47.8	20
20-24	8.2	50.3	36
24-28	8.4	51.5	37
28-32	8.6	52.8	6



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But, it's not just about bucket size and contents, it's also about suction

- If water is non-limiting, actual evapotranspiration (AE) matches potential evapotranspiration (PE) after adjusting for K_c
- As the soil dries out, AE falls below PE as the root system cannot access water fast enough to satisfy PE
- The form of this relationship is altered by the magnitude of daily evaporative demand
- Acknowledges ideas of Makkink & Van Heemst (1956), Denmead & Shaw (1962), Bailey & Spackman (1996)
- Re-thought and published by Stalham & Allen (2005)

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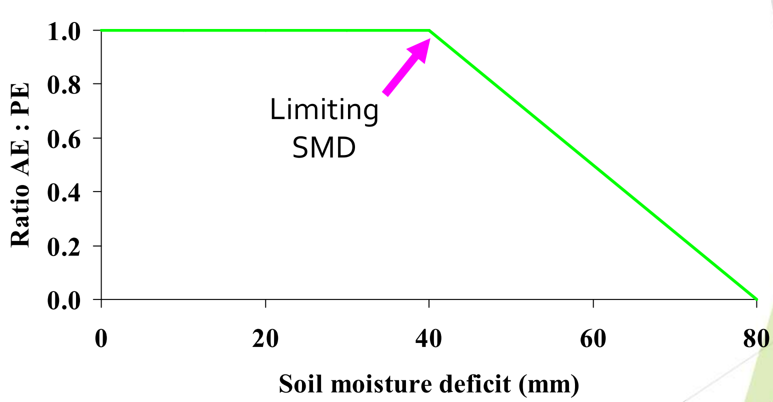
Penman's approach to limiting deficit



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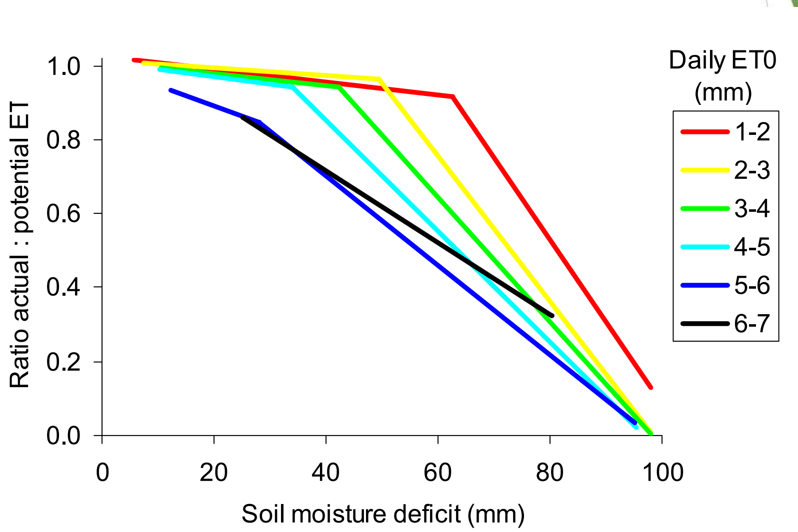
Daily water use depends on both SMD and rate of ET



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Response to irrigation

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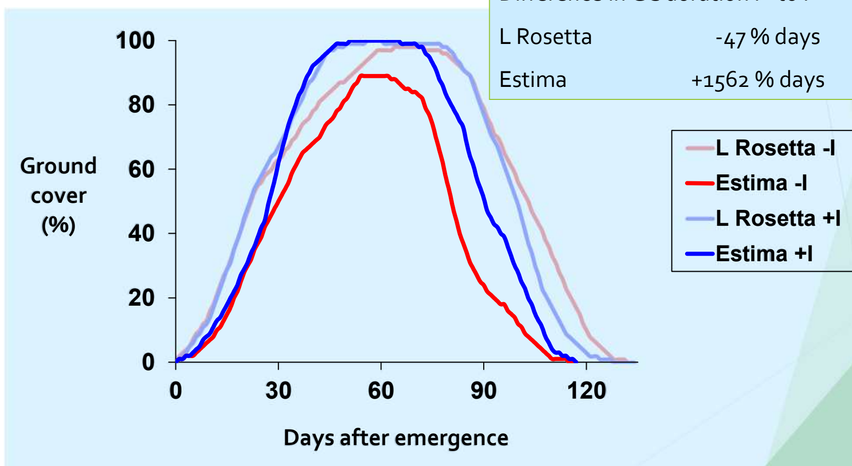
Estima vs L Rosetta 2004-2007 Unirrigated vs Irrigated

Difference in GC duration I+ to I-	
L Rosetta	-47 % days
Estima	+1562 % days



Source: Stalham 2004-2007; Firman 2004-2007

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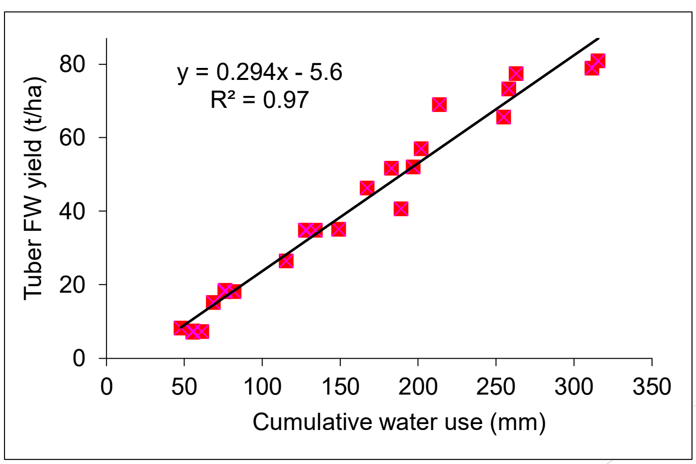
Russet Burbank: yields continue to increase as water use increases



Source: Gaze & Stalham 1997

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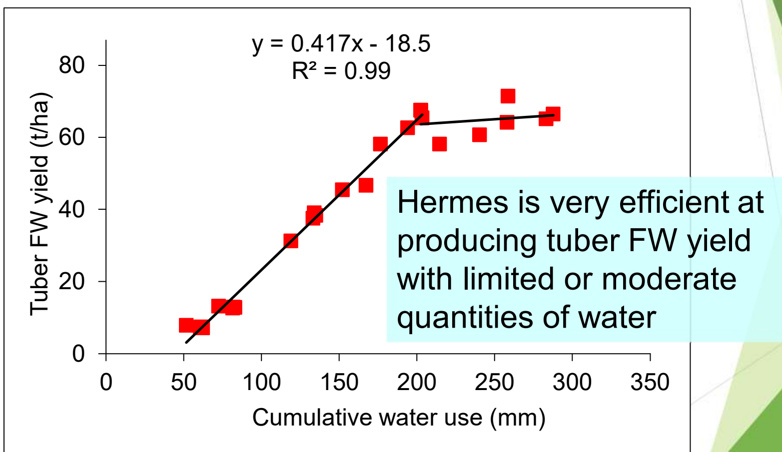
Hermes: crops using >200 mm water have similar yields



Source: Gaze & Stalham 1997

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Irrigation scheduling – the (simple) questions

Questions

a) When to apply?
b) How much to apply?
c) How to apply uniformly?

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Irrigation scheduling is simply about satisfying a water balance

Change in soil water storage (ΔS) =

(ET + drainage + runoff) –
(rain + irrigation + run-on + capillary rise)

ΔS = SMD if Field Capacity (FC) is the starting point. Instruments estimate SMD by measuring soil water content

FC is the amount of water held in a soil after gravitational water has drained away

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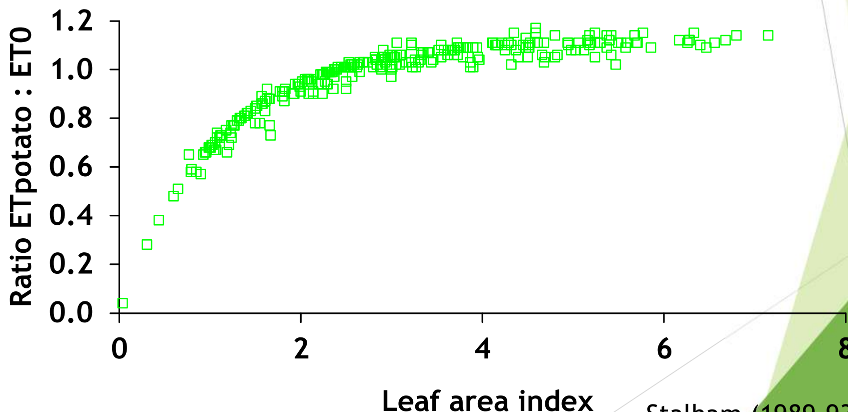
K_c for potatoes:

1.12*Reference Crop
(rougher, taller, higher stomatal resistance than grass?)



Stalham (1989-93)

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niab digital
Powered by KisanHub

Potato Crop Management

- Photos of crops are uploaded automatically and processed to calculate the percentage ground cover

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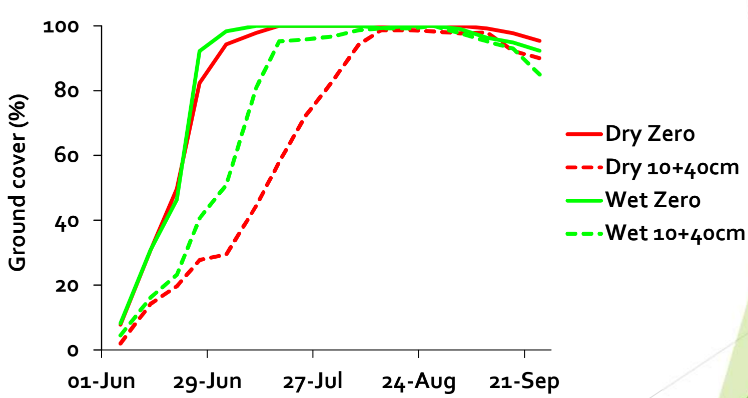
Effect of irrigation and compaction on ground cover



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Average ET from full canopy cover of potato in June-August

- 3.27 mm/day
- 22.9 mm/week
- ≈ 25 mm/week allowing for 10 % evaporative loss when irrigating
- Maximum measured water use in potatoes
  - UK 6.6 mm
  - USA 9.1 mm

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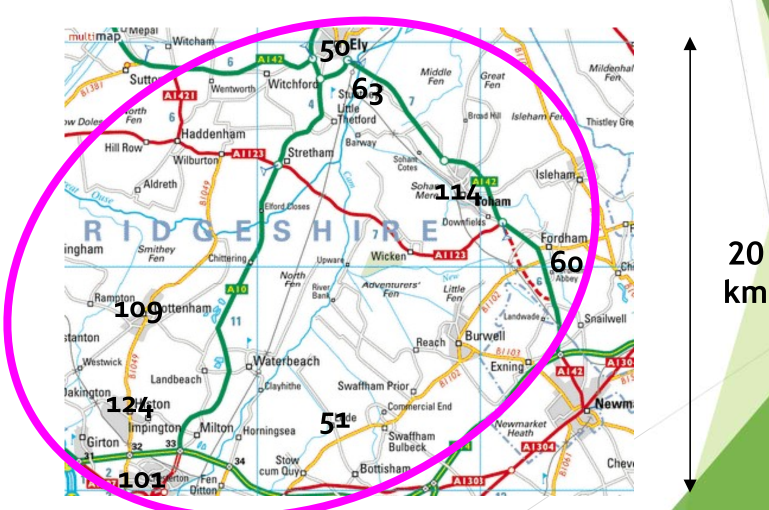
Variation in rainfall, June 2002. We need to record accurately



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Climate change

Scenarios for 2050

- Warmer: growing season lengthened by 5-6 weeks
- Earlier planting
- More rapid emergence and ground cover expansion
- Determinate varieties will senesce earlier
- Longer spells of drought
- More extreme rainfall events (341 mm/day!), but likely to be in the winter not summer

brisbanetimes

World

'Biblical' floods engulf England's north

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Record rainfall 'would have overwhelmed any defence'

ENGINEERS BEGIN URGENT REVIEW OF COUNTY'S 1,800 BRIDGES HIT BY FLOODWATER

Published: 23/11/2009

The unprecedented rainfall which devastated parts of Cumbria 'would have overwhelmed any defence' the Environment Agency said yesterday.

Structural engineers and military experts began an urgent safety review of the county's 1,800 bridges as fears grew that Calva Bridge in Workington was on the brink of being swept away.

The coastal town was cut off, with Friday's collapse of Northside

Scenarios for 2050 (water use)

- Evapotranspiration (c.f. 1968-1990) Low vs High emissions
  - Less cloud cover = increased solar radiation = more ET energy
  - 15-20 % increase in ET
  - Increased demand for irrigation?
- But:
  - CO_2 increase from 350 to 550 ppm
  - Increased growth rate (+20-30 %)
  - Reduced stomatal aperture = increased water use efficiency (+25-30 %)
  - Balances out so only 20-25 mm more water required per season
  - Can we manage on existing supplies?

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Can we manage on existing resources?

- No
- Think 4.5 mm/day for potatoes in UK, not 3.5 mm
- Will need slightly more water, but earlier and at an increased rate of abstraction
- Problem with new licencing with respect to daily abstraction limits
- Competition between abstractors: power, domestic, data centres, spray irrigation only 0.5% of total abstraction
- Use it or lose it (only 67% of licenced volume abstracted between 2000 and 2018 on average; 116% in 2018; close to 90% in last 5 years)
- More application capacity required

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Scheduling

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Definitions used in scheduling

- Potential ET_{pot} = water use by crop with unrestricted water supply
- Actual ET_{act} = water use by crop with irrigation schedule being used
- SMD = soil moisture deficit
- SMD descriptors:
  - Limiting SMD: when crop water use slows below the potential as the soil is too dry
  - Critical SMD = when crop growth stops and failure to water will cause crop to die
  - Allowable SMD = management-restrained Limiting SMD, e.g. it takes 7 days to irrigate field, so aim is to finish before Limiting SMD is exceeded
  - Scab SMD = maximum permissible SMD in tuber zone to prevent common scab infection
- Irrigation = amount reaching crop canopy
- Drainage = loss below rooting zone

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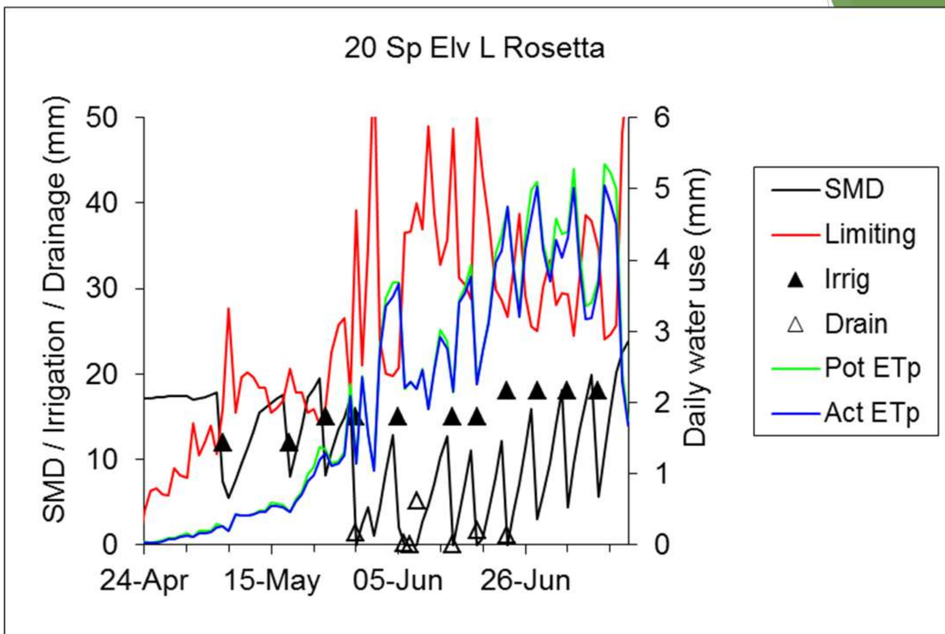

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20 Sp Elv L Rosetta, Norfolk, UK

- 32.6 t/ha
- 171 mm irrigation applied
- 4 mm drainage
- 197 mm (96 %) of potential water use met to 11 July (excellent)
- Well-scheduled (typically 15 mm SMD)
- Could have started each irrigation 2 days later to run *c*. 20 mm SMD

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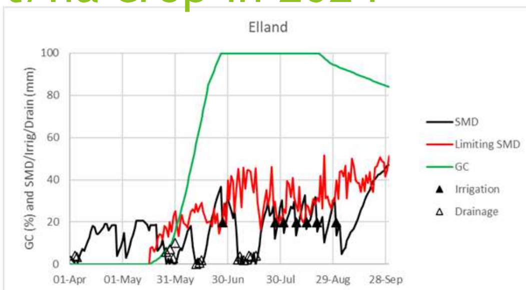
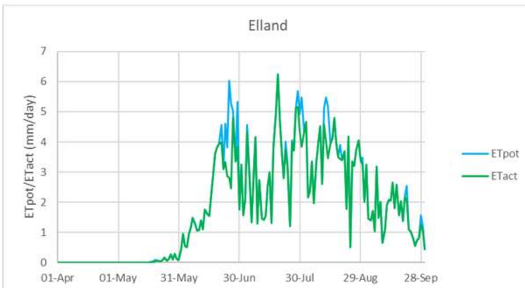
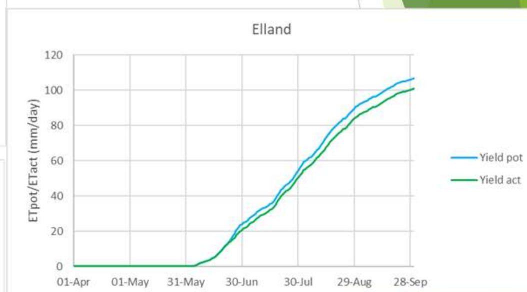
Dynamic demand. Meeting the needs of a 100 t/ha crop in 2024







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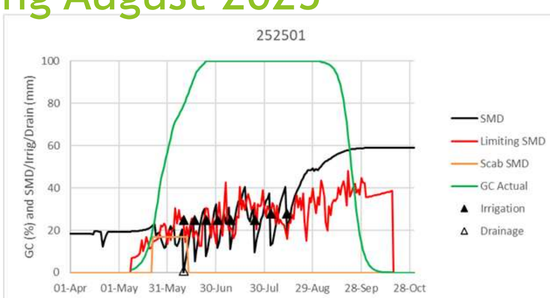
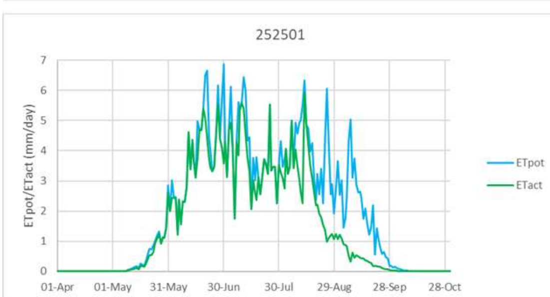
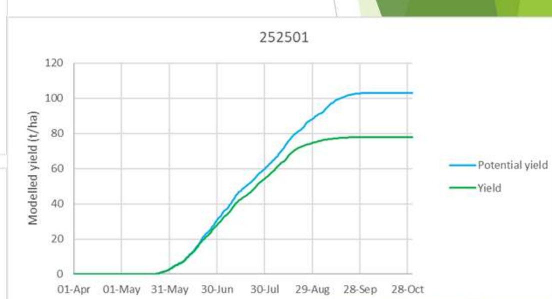
Dynamic demand. NOT meeting the needs during August 2025







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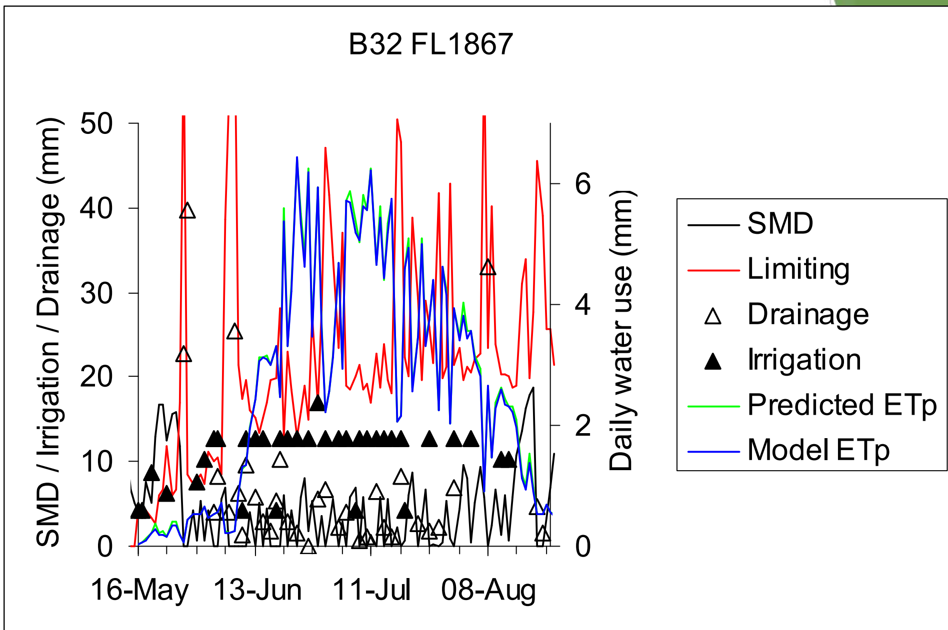

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B32 FL1867, Wisconsin, USA

- 55.1 t/ha
- 371 mm irrigation applied
- 245 mm drainage (four events 23-40 mm caused by rainfall) but most ½" irrigations caused *c.* 5 mm drainage
- 262 mm (99 %) of potential water use met to 23 August (excellent)
- Actual SMD maintained < 10 mm throughout most of season whereas Limiting SMD typically 20 mm (similar observations made in 2008)
- Could run soil slightly drier (15-20 mm SMD)

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Breakout: a test on understanding! Scheduling model test, Cambridge, UK

Maris Piper	1989 - 2025			
Emergence	24-May			
Irrigation regime	No scab control			
Value (£/t)	250			
	1	2	3	4
Maximum SMD (mm)				
Irrigation amount (mm)				
Irrigation applied (mm)				
Yield (t/ha)				
Drainage (mm)				
Irrig. effic. (t/ha/mm)				
Margin over irrig. (£/ha)				

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Training Course

Irrigation #2

March 2025

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Soil water measurement

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Smart tools: a small selection!

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Scheduling technique	Advantages	Disadvantages
1. Soil water measurement	Easy in practice (e.g. automated);	Soil/root heterogeneity requires many (expensive) sensors
(a) Potential (e.g.tensiometer)	Reflects soil/plant water	Does not advise on how much to apply
(b) Content (e.g. capacitance)	Accurate; readily automated	Small sphere of measurement
2. Water balance calculations	Simple; advises how much to apply	Not as accurate as direct measurement; needs accurate Kc/rain/irrigation data
3. Plant 'stress' sensing	Measures plant stress response directly; potentially very sensitive	Does not advise how much to apply; calibration required; research tools
(a) Tissue water status	Best for physiological processes but ignores root-shoot signalling	Sensitive to environmental conditions which can lead to large fluctuations
(i) Visible wilting	Easy to detect	Not precise; yield already reduced
(ii) Pressure chamber	Widely-used reference technique	Slow and labour intensive
(iii) Psychrometer	Can be automated	Sophisticated equipment/technical skill
(iv) Tissue water content	Easier automation c.f. water potential	Instrumentation complex/expensive
(v) Pressure probe	Estimates xylem flow and cell growth	Laboratory only
(vi) Xylem cavitation	Sensitive to increasing stress	Not work in reverse i.e. re-hydration
(b) Physiological responses	More sensitive than tissue measures	Complex equipment; requires calibration
(i) Stomatal conductance	Very sensitive response	Large inter-leaf variation (high replication)
• Porometer	Accurate benchmark	Labour intensive

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Measuring soil water content for scheduling

- Can the device measure SWC **accurately**?
- How **precise** is it? (i.e. how **representative** are the measured points of the **crop** in the field?
- Is it robust?

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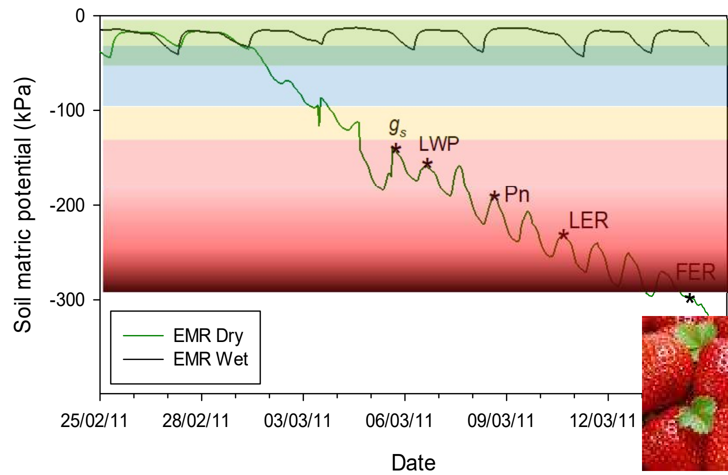
Deriving irrigation set points for field-grown 'Elsanta' strawberries (Else *et al*. 2012)



Commercial Grower test regime

Buffer zone

Mild RDI

Quality and yields reduced…

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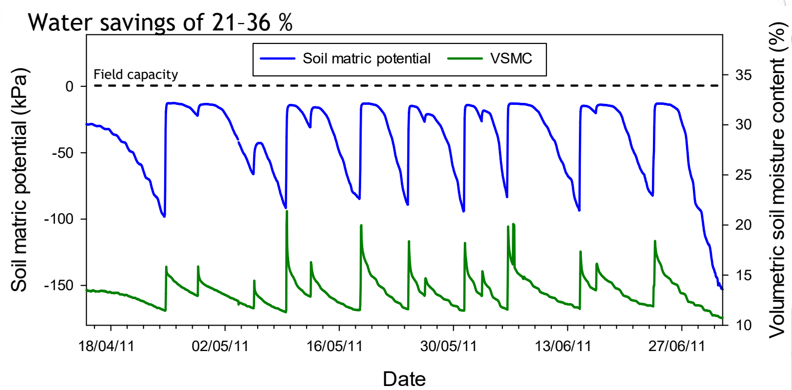
Higher Class 1 yields under Grower Test Regime

- **100 KPa not 30 KPa refill**
- Water savings of 21-36 %



- Class 1 yields of ~23 t/ha (15 % increase)
- Water productivity = 27 l/kg (27 % decrease in water per kg)
- Bigger, firmer, better-flavoured (M&S) berries

58

Problems with measuring instruments

- Spatial positioning with respect to plant arrangement and soil profile?
- Depth (often not deep enough to measure contribution made by deep roots)?
- Accuracy – are we really measuring all the water?
- Field capacity – when to determine (slumping, deep drainage)
- Replication?
- Droughtiest areas of soil or average; slopes; irrigation runs etc?
- [Calibration?]
- [Disturbance to soil and crop during installation/reading?]

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Rooting volume

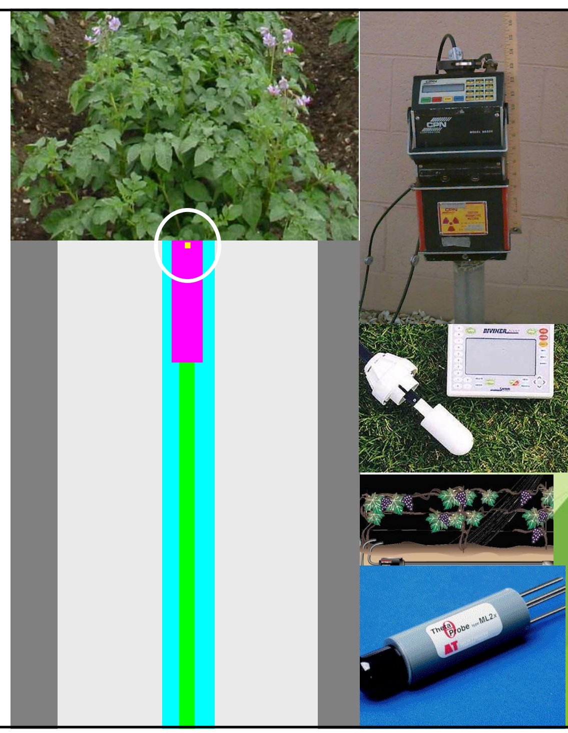
Neutron probe (dry)

Neutron probe (wet)

Diviner/EnviroSCAN

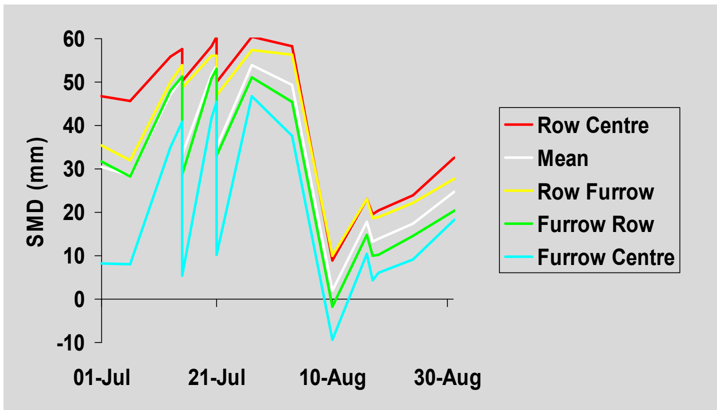
Aquaflex

Theta Probe/WET Sensor/SM200



60

The 'standard' row centre position is always drier than the mean which leads to over-irrigation. There is no single ideal location in the ridge.



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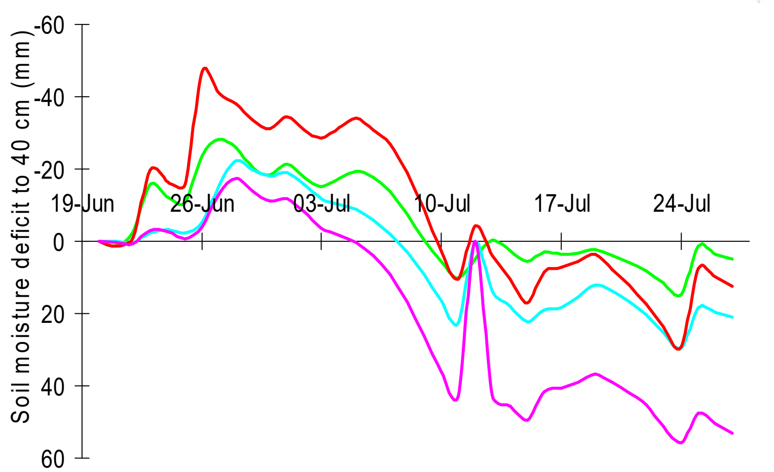
Replication? Four ES tubes receiving the same irrigation and rainfall (1997)



± 10 mm = 4 tubes ± 5 mm = 9 tubes

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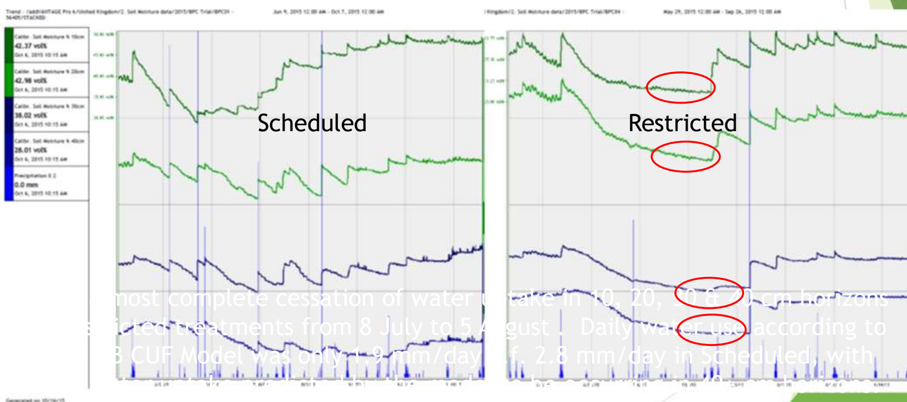
AHDB SPot Farm West 2015
Agrii Soil Moisture Probe Plots



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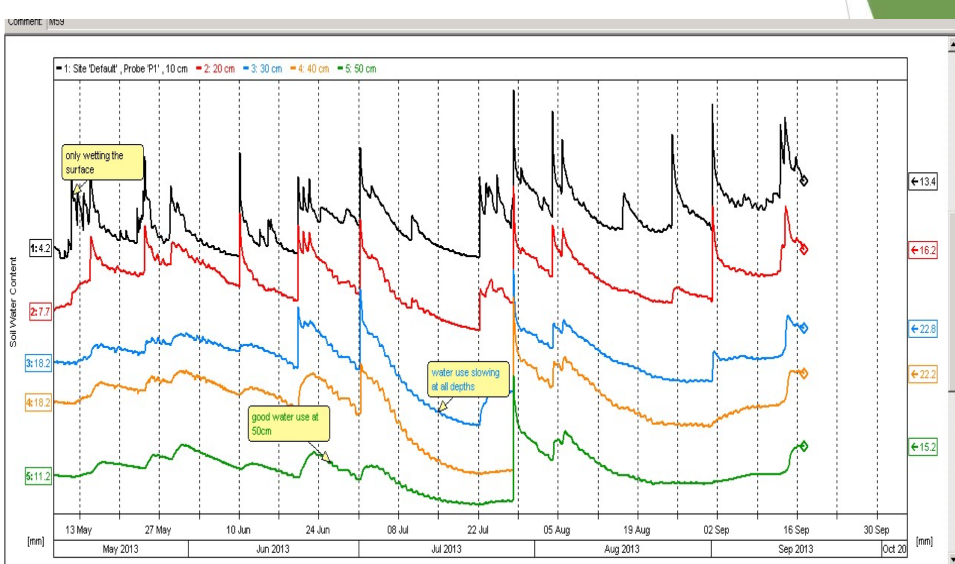
Example of EnviroSCAN plot:
M59 – Much lighter soil. Excellent deep water use to 50 cm



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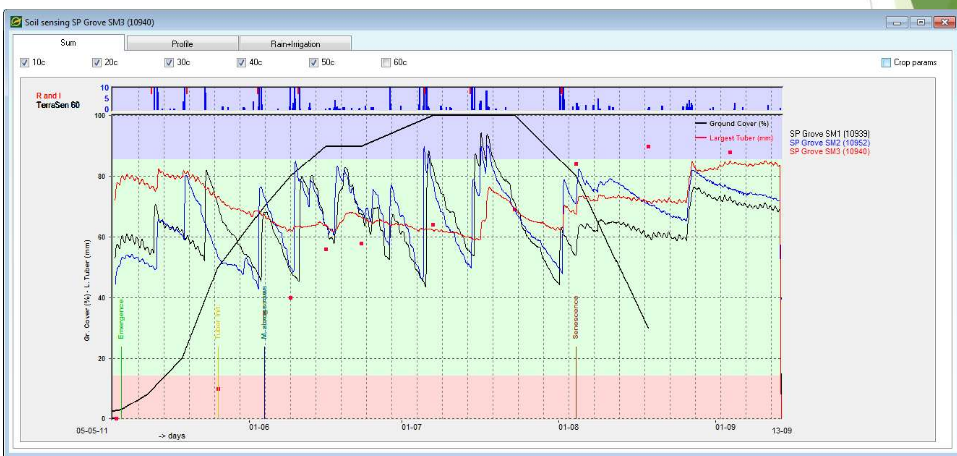
Large variations in water content and responses to water between replicates and very different response on SM3



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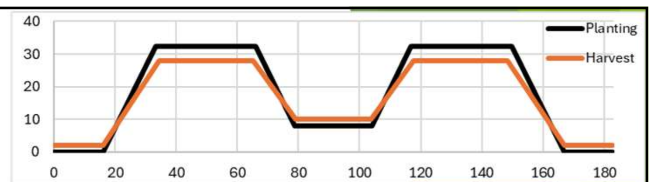
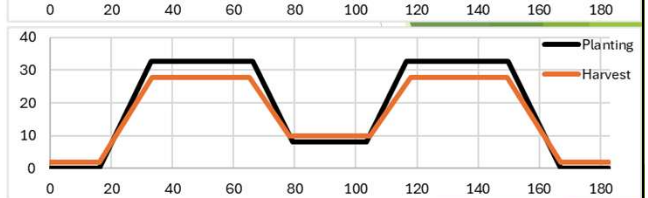
Change in ridge profile: LITE 2024 Yorkshire (All axes in cm)

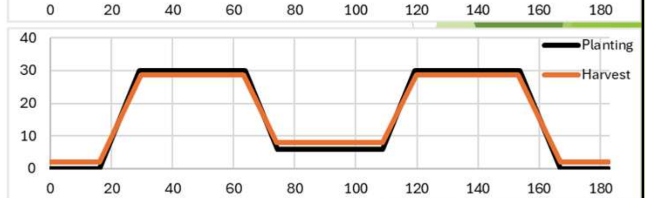
Conventional



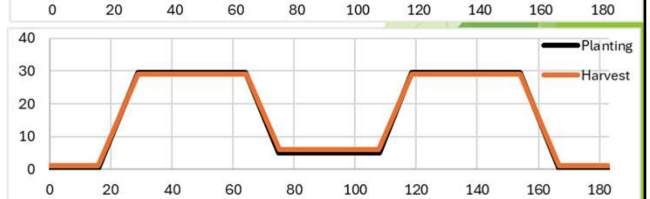
Alternative Destoner



Rotary



Fixed Tine



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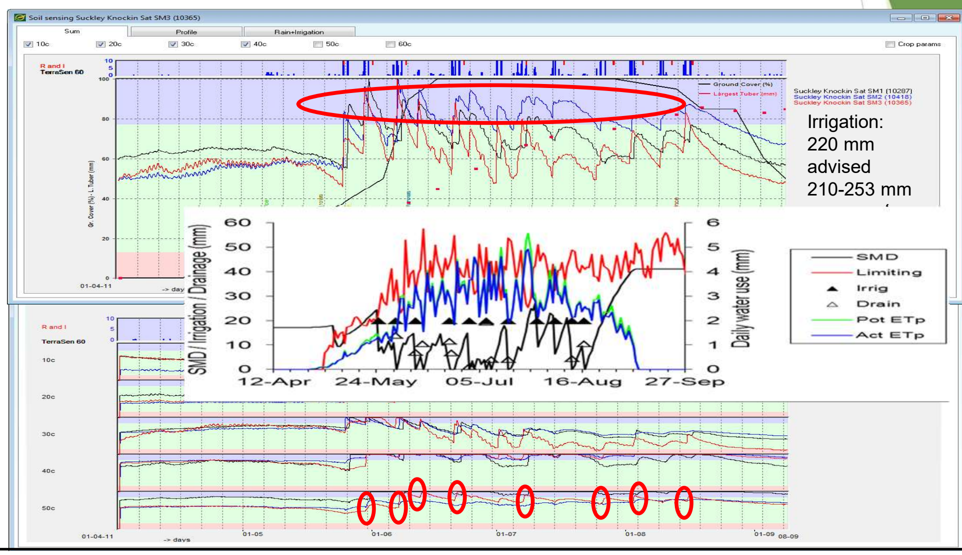
Example of over-irrigation showing drainage events at each irrigation, supporting model data



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Application

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Equipment usage by area (2010)

- Hosereel + raingun 76 %
- Hosereel + boom 17 % (moving slowly upwards)
- Drip 4 % (still <5%)
- Solid set sprinklers 2 %
- Centre pivot and linear move 1 %

Source: Defra (2011)

69

Aerial application equipment

70

Pressure requirement for typical irrigation systems

Most pipe systems	12 bar
Hosereel	5.5-10 bar
Rainguns	4-5 bar
Booms	2-4 bar
Sprinklers	2-4 bar
Drip	0.5-1 bar

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Raingun operation

- Raingun operation – system pressure
- Biggest single problem is often incorrect pressure (i.e. low) at the gun
- Results in:
  - Poor atomisation – many larger drops
  - Poor distribution
  - Higher energy impact on soil / plant
  - Overall shorter throw of water
  - Wind worsens all these factors
- 210° better than 180° as gun lingers on reversal
- Variable or low trajectory (15-25°) guns can provide advantages in windy, exposed conditions

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Pressure, flow and throw (26 mm nozzle)

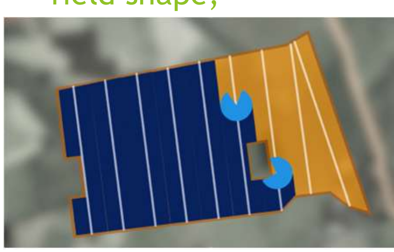
Gun pressure (bar)	Flow (l/s)	Radius (m)	% throw vs 4.5 bar
3	13	42	86
3.5	14	45	91
4	14	47	96
4.5	15	49	100
5	16	51	104
5.5	17	53	108
6	18	55	112

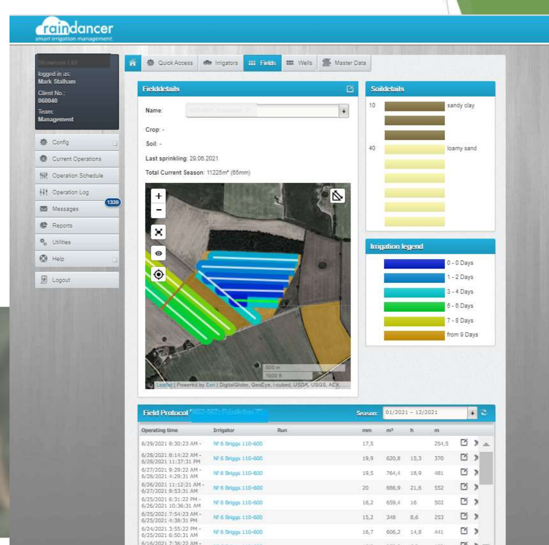
Aim for 30-35 % over-lap

73

raindancer

Volumes per run and inefficiencies: field shape,





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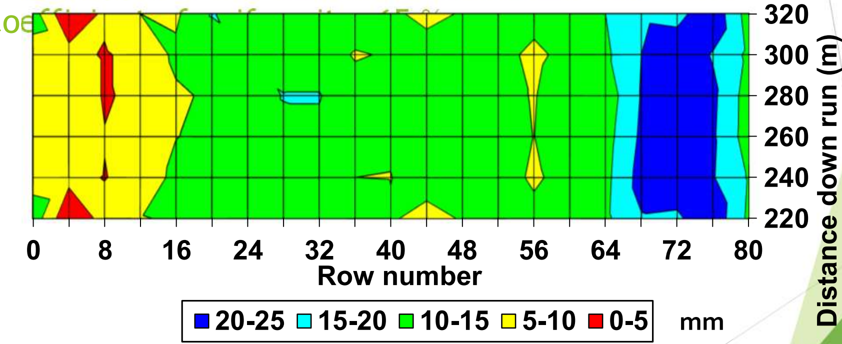
Irrigation distribution pattern of Wright Rain ST350/Nelson gun combination. Three adjacent runs, two day-time, one night-time. Conditions: wind 20 km/hr day, 1 km/hr night. Target application: 12.5 mm. Achieved: 12.5 mm.
Coe



75

Boom operation

- Increasing use on high-value crops
- Uniform droplet size
- Very low crop damage / soil splash
- Application uniformity usually >90 %
- Less prone to wind effects (drift reduces amount uniformly rather than erratically)
- Operate at 2-4 bar (4 bar if raingun at end of boom)
- Higher initial cost
- Slower to move
- Field 'furniture' issues
- Not suited to soils with low infiltration rate

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Infiltration rates

Category	Equilibrium Infiltration Capacity Range (mm/h)	Soil texture
Very high	> 100	Coarse sands, sands, loamy coarse sands and loamy sands
High	20-100	Sandy loams, fine and very fine sandy loams, loamy fine sands and loamy very fine sands
Moderate	5-20	Sandy clay loams, silts loams, silty loams and clay loams
Low	< 5	Clays, silty clays and sandy clays

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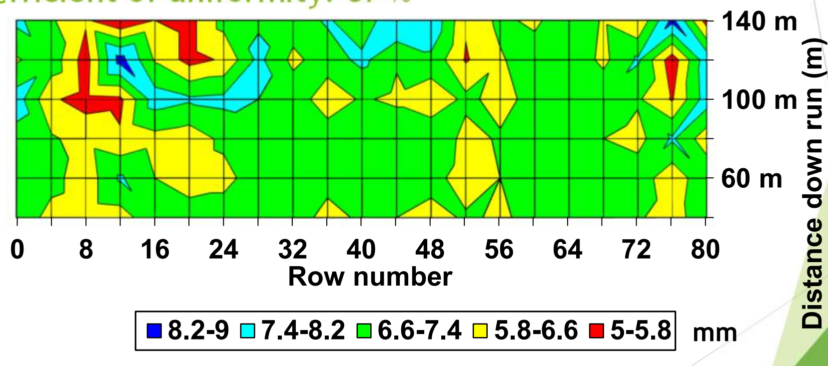
Irrigation distribution pattern of Briggs R50 boom + Ocmis R4/100/450. Two adjacent runs, both day-time. Conditions: wind 25 km/hr. Target application: 8 mm. Achieved: 6.7 mm. Coefficient of uniformity: 87 %



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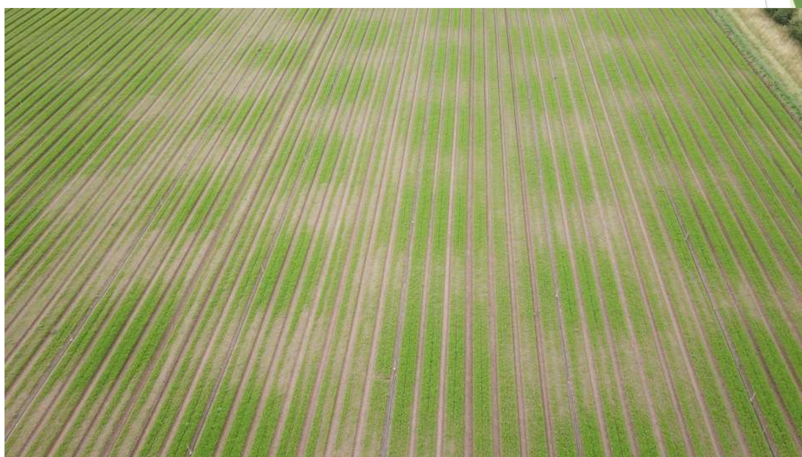
Spot anything wrong (not just the carrots)?



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Coefficient of uniformity

- Checking application uniformity
- Place catch-cans or buckets at 3 m intervals across at right angles to the direction of pull and fully across the distribution area
- For a rain gun operating at 72 m lane spacing is around 85 to 90 m so 30 cans will be required
- Run the irrigator over the area then measure and record the volume of water in each catch-can
- Use the following formula to calculate uniformity
- $CU=(1-(\Sigma(x\text{-}xm))/y)\times 100$

80

Measured vs advised irrigation

- 28 crops being monitored with SM probes received irrigation from an aerial (i.e. non-drip) source and had 3 probes recording
- Extracted raw SM data and compared RG1-3 data with weather station rainfall
- Meaned over all crops, there was an underestimate of amount applied (79 mm) vs advised (94 mm)
- Analysis demonstrated:
  - Under-recording mostly due to under-dosing and missed events
  - Serious over-dosing (+10 mm) at each irrigation on some fields
  - Uncovered irrigation events that were not advised
  - Timing differed by several days in some cases
  - On 11 crops the difference was > ±20 mm (maximum difference 91 mm)
  - On 9 crops the difference was > ±30 mm (2013 > ±30 mm on 14 out of 33 fields)

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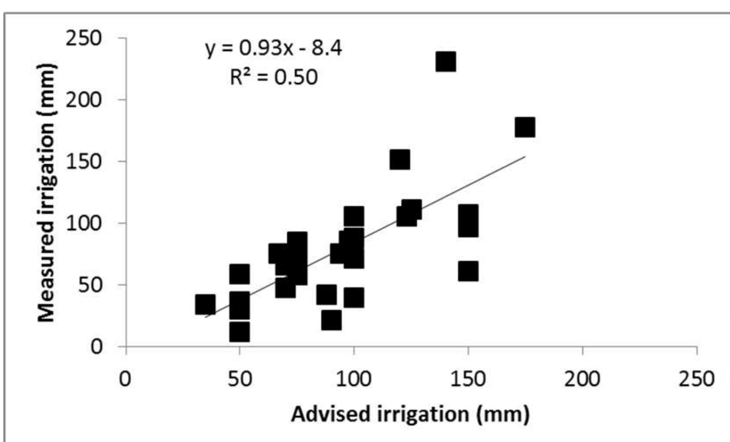
Measured vs grower-advised irrigation, summary

	Irrigation (mm)	Water use (mm)	Drainage (mm)	Potential (%)
Measured	79	191	65	91
Advised	94	195	73	93



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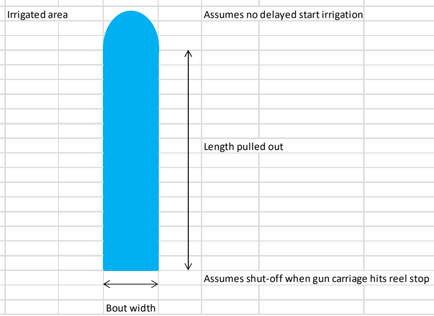
Simple flowmeter attached to inlet of hosereel (you know how much but not where)

Grower	Field	Bout (m)	Run no.	Date	Time start	Length pulled out (m)	Wind-in speed (m/h)	Start flowmeter (m3)	Finish flowmeter (m3)	Water used (m3)	Depth (mm)	Pre-Irrigation (min)
GFP	Cley Way	72	1	06-Jun	10:00	465	35	7.00	646.00	639.00	18.0	13.71
GFP	Cley Way	72	2	07-Jun	09:30	465	35	646.00	1303.00	657.00	18.5	13.71
GFP	Cley Way	72	3	08-Jun	08:30	465	35	1303.00	1972.00	669.00	18.8	13.71
GFP	Cley Way	72	4	09-Jun	09:30	465	35	1972.00	2700.00	728.00	20.5	13.71
GFP	Cley Way	48	5	09-Jun	12:16	153	35	2700.00	2941.00	241.00	29.2	13.71
										Average	18.4	



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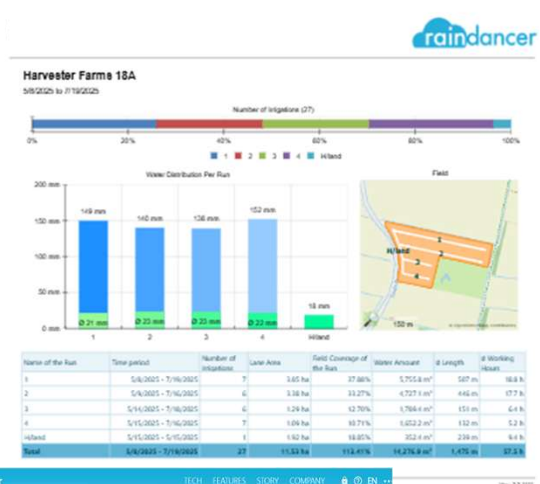

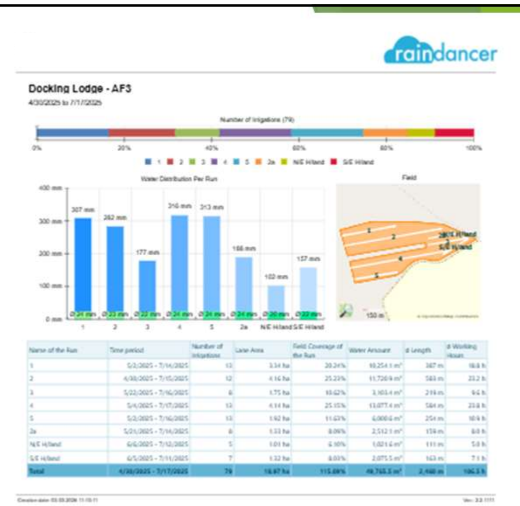

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Solid-set sprinkler systems

- New plastic types – 12 m–18 m spacing
- Plastic headers for season long use
- Low pressure – good uniformity
- Small doses possible (5-10 mm)
- Suits small areas or awkward fields
- Cost can be higher than some systems
- Must be laid out each season

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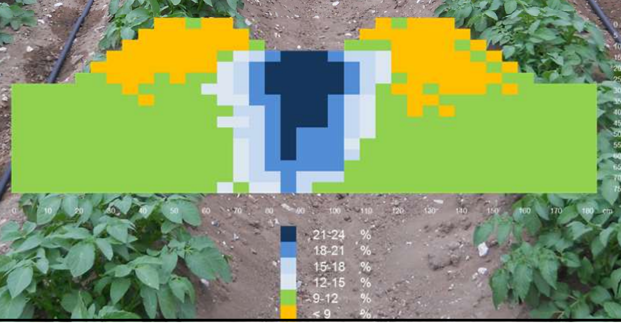
Drip

- Low energy and pressure
- Controlled 'uniform' wetting?
- Less evaporation
- Need to match emitter spacing and flow rate to soil profile and texture otherwise localised wetting
- Need to monitor carefully: easy to over-irrigate
- High cost



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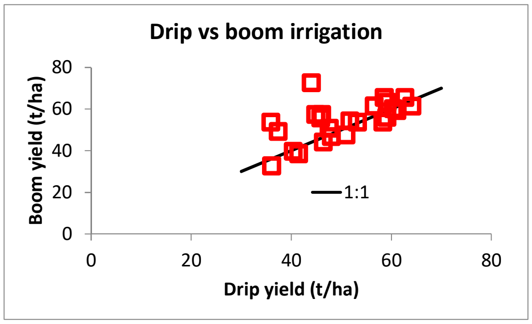
Drip vs overhead comparison summary 2011-2015



- Drip: lower yields (-3.5 t/ha) overall *c.f.* boom/gun but 40 mm less irrigation applied and irrigation usage 6300 l/t lower
- Poor irrigation management on 5 sites led to very dry soils and premature canopy death

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Drip: increased yield or savings in water?

- Both possible
- Single line vs double line per bed
- ICrop survey data (n=24): 32 % saving in water
- But 3.5 t/ha (6 %) decrease in yield

Treatment	Yield (t/ha)	Irrigation (mm)	IUE (t/ha/mm)
Unirrigated	37.5	0	
Drip x 1	59.6	73	0.30
Drip x 2	71.9	146	0.24
Boom	70.5	143	0.23

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Manage wheelings to prevent run-off

Source: Silgram (2012)

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Summary

- Crop water use is determined by evaporative conditions, canopy size and soil water status
- Modified Penman-Monteith equations can accurately predict crop water use where soil water supply is both unlimited and limited
- Instruments which measure SWC would be useful to collect data under conditions of limited soil supply, restricted rooting, compaction and high ET demand
- But can we trust current instruments to give us an accurate measure of overall SWC?
- We need to monitor irrigation application more closely

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Effects of irrigation on tuber quality

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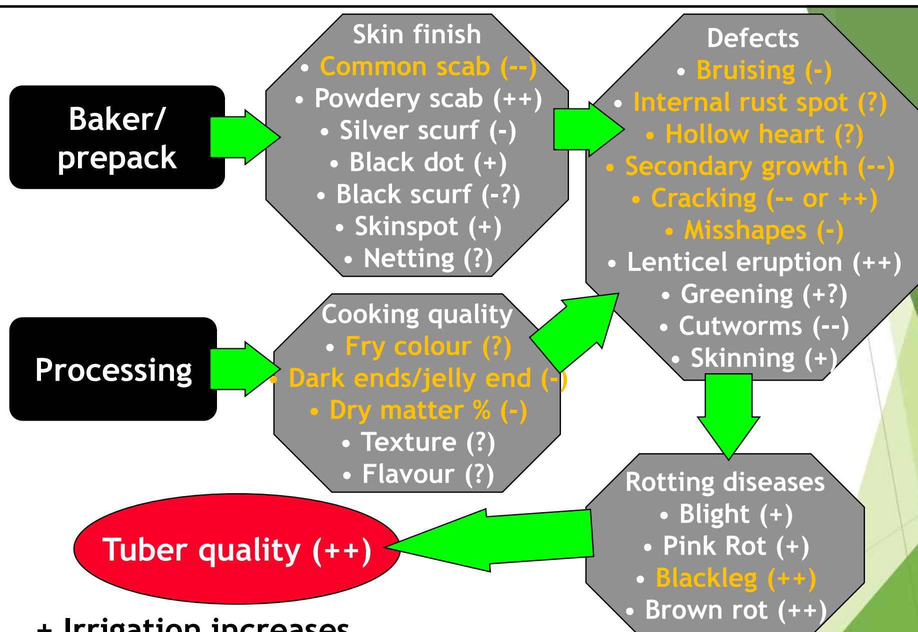

+ Irrigation increases

- Irrigation decreases

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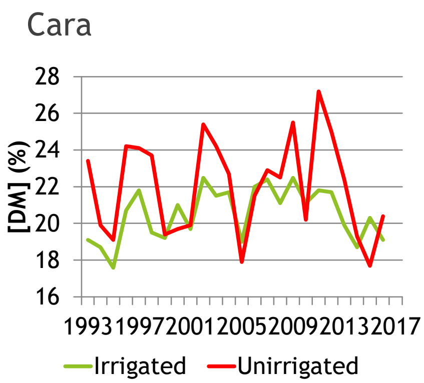
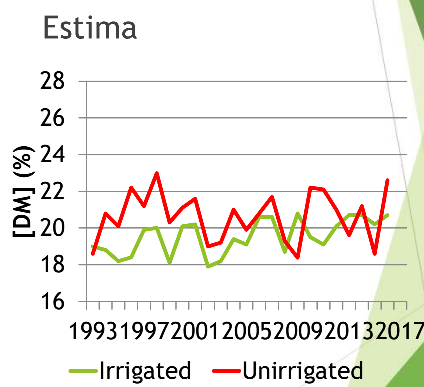
Effect of season, variety and irrigation on tuber [DM]





Source: CUF Reference Crop

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Common scab – *Streptomyces scabiei*
Erumpent or raised corky scab

94

Common scab irrigation

- Soil in ridge needs to remain moist to wet to prevent build-up of pathogenic *Streptomyces*
- Reduction in *Streptomyces* is almost certainly due to a relative shift in other bacterial and fungal populations that act as antagonists, but situation is unclear what is happening despite 5 years of work at CUF and FERA
- Key period is weeks 1-3 post tuber initiation
- Over-wet soils will encourage lenticel eruption and turgor-induced cracking

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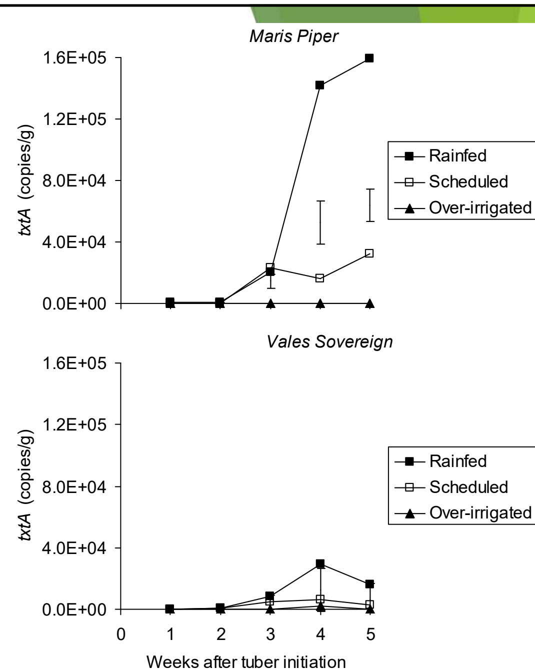
Increase in pathogenic *Streptomyces* populations is greater in dry soils than wet and smaller in more resistant varieties than very susceptible



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Common scab irrigation – when to start

- In sensitive varieties, if soil is dry, start irrigation when FIRST plants begin to initiate; 50 % initiation will be 3-5 days behind allowing time to complete field
- When growing the least sensitive varieties, can start at 1 week after initiation
- Ridges may be dry following first irrigation and a repeat application may need to be made within 3-4 days: observe by digging
- Pre-irrigate hydrophobic, capped or cloddy soils 1-2 days before onset of initiation, not 7 days before

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Common scab irrigation – amount

- Based on allowable SMD
- Maximum applications:
  - sand 10 mm
  - sandy loam 15 mm
  - clay loam 15 mm
  - silt loam 18 mm
- Little recent evidence that maintaining soils close to field capacity improves scab control compared to maintaining a 10-18 mm SMD, particularly for less susceptible varieties

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Common scab – when to stop

- Maincrops: 21-48 days post TI (depending on duration of emergence and variety): average 31 days
- Delayed by delaying onset of tuber bulking through excessive N and disease e.g. *Rhizoctonia*
- Stopping after 2 weeks can allow infection of apical end of tuber
- 4 weeks mostly better than 2 weeks, but 3 weeks can be similar to 4 weeks (depends on QA tolerances)
- Work on salads has shown that 6 weeks is adequate for Maris Peer and 4 weeks for Venezia and Regina
- Scab control for processing varieties: between 1-3 weeks after TI
- Can increase allowable SMD for yield from 10-18 mm to 30-50 mm immediately once control period over
- Powdery scab risk is increased but continuing too long

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Common scab control in different varietal scheduling groups

Notes:
Soil moisture deficit (SMD) for top 25 cm of stone-free ridge profile. This can be calculated by water balance ('model'), directly measured or converted from soil water tension.

†Excessively cloddy soils may need to be maintained at a smaller SMD.

Values in () are the rankings for common scab resistance in AHDB Potato Variety Database. 1 = most susceptible, 9 = fully resistant.

Varietal scheduling group

1. V. Susceptible	2. Susceptible	3. Intermediate	4. Resistant
Maris Piper(1)	Charlotte (4)	Bute (4)	Electra (8)
Maris Peer (5)	Desiree (4)	Estima (6)	Elfe
	Leontine	Exquisa	Jelly (6)
	Marabel	Flair	Lanorma (7)
	Nectar (4)	Juliette (7)	Orchestra (8)
	Red Fantasy	King Edward (7)	Perline
	Rooster (6)	Melody (7)	Regina
	Safari (4)	Soraya	Vales Sovereign (7)
	Saxon (5)	Sylvana (7)	Volare (5)
	Venezia (3)		
	Vivaldi (5)		

Soil texture	Maximum soil moisture deficit (mm)			
Sand	9.8	12.7	15.6	18.8
Loamy Sand	12.0	15.9	19.3	23.1
Sandy Loam	13.4	17.8	21.5	25.8
Sandy Silt Loam	14.4	19.0	23.0	27.7
Silt Loam	16.3	21.5	26.2	31.4
Clay Loam/Clay†	14.4	19.0	23.1	27.7

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Soil texture in relation to pre-pack quality

Texture	Pre-pack suitability (stone free) 1 = poorest, 10 = best	
cS	1	
mS	2	For common scab, finer textured soils are better, but clay dominated soils crack on drying
fS	4	leading to greening.
LcS	3	Sand fraction determines storage potential, since abrasion of tuber skin by sharp (angular)
LmS	4	sand grains reduces lustre after storage even though tubers may appear bright at harvest.
LfS	6	Fine, rounded sand grains are better.
cSL	5	
mSL	6	Gritty or sharp sand reduces score by 1 point.
fSL	7	
vfSL	10	A calibrated "feel" of the soil between forefinger and thumb is still the best method!
cSZL	7	
mSZL	8	Stones do not necessarily ruin pre-pack quality, even if present in the ridge.
fSZL	9	
ZL	10	Pathology issues can drop score by 1-2 points e.g. sequential cropping or known disease -2,
ZCL	9	short rotations -1, virgin land 0.
CL	7	
SCL	8	Higher scoring samples are more suitable for long-term storage.
SC	8	
ZC	8	
C	8	
Z	10	
P	7	

S = sand, C = clay, Z = silt, L = loam, P = peat, c = coarse, m = medium, f = fine, v = very

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Cracking symptoms Maris Piper

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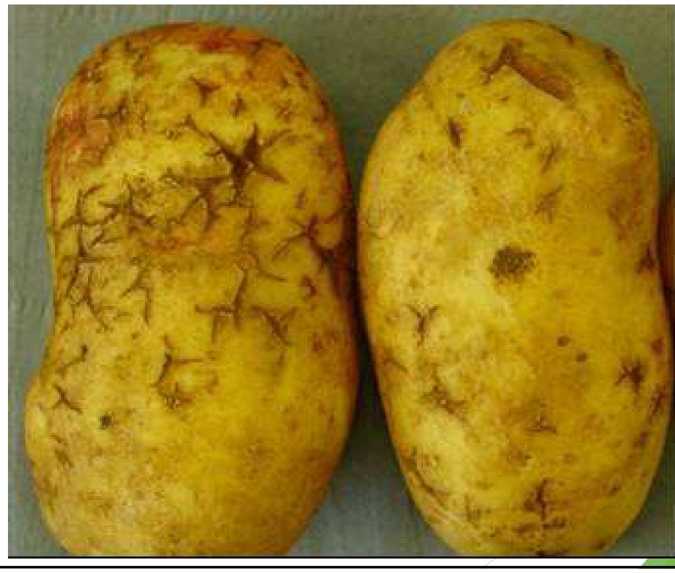
Cracking symptoms
Vales Sovereign



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Risk of cracking from over-watering during scab control

	Group	
1. High risk	2. Moderate risk	3. Low risk
Safari Estima Vales Sovereign Melody Orchestra Nectar Maris Piper Lanorma Bute Sylvana	Flair Jelly King Edward Maris Peer Volare	Desiree Elfe Exquisa Marabel Perline Regina Venezia Vivaldi

Ranked in each Group by risk

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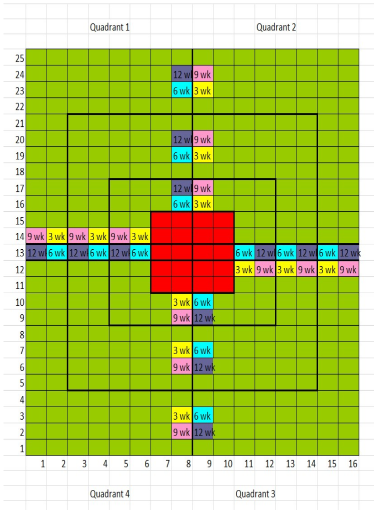
Movement of *P. atrosepticum* within fields

- Tracking the spread of *P. atrosepticum* in the field over 3 years



- Grown from mini-tubers
- No obvious pattern of spread from the marked central zone
- Progeny tuber contamination and blackleg was caused by natural pectobacteria as well as marked strains
- Blackleg appeared with irrigation

The James Hutton Institute

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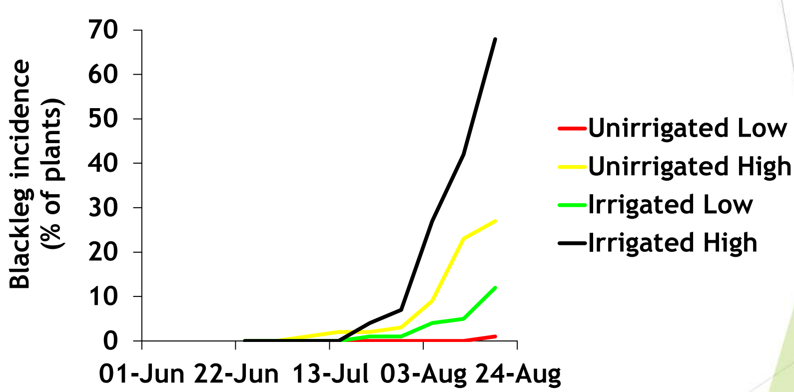
Effect of irrigation regime and seed contamination level on blackleg infection



Source: Firman (2003)

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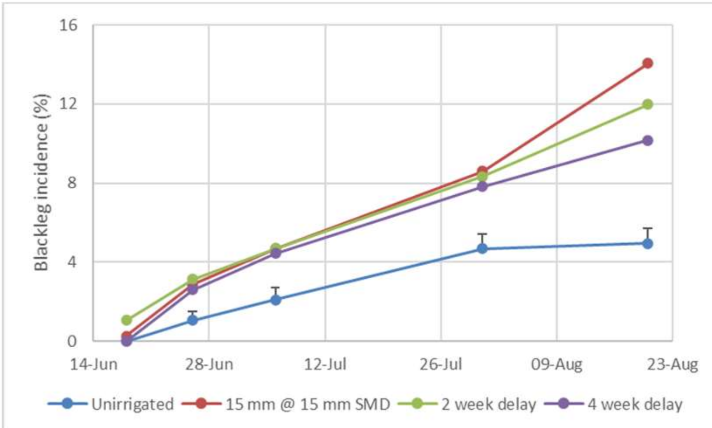
Effect of irrigation regime on blackleg development: delaying irrigation after scab control period (BBSRC Blackleg DSS, 2020)



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Brown centre and hollow heart

- Internal non-infectious physiological disorders
- Region of cell death in the pith
- Hollow heart is characterized by a star- or lens-shaped hollow in the centre of the tuber
- Hollow heart may occur without being preceded by brown centre
- Probability is based on rate of tuber growth following a stress period (Hiller *et al*. 1985)
- Fast-growing, large tubers have greatest risk

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Brown centre and hollow heart (R Burbank)

- Susceptibility greatest soon after TI (McCann & Stark 1989)
- Avoid soil water content > 80 % of field capacity (Bussan 2008)
- Avoid periods of dry followed by large irrigation events (Selman *et al*. 2008)
- Consistent soil water content is key (Hiller & Thornton 2008)
- Adherence to management profile for variety:
  - Avoid early irrigation
  - Delay the first application until 2 weeks after tuber initiation, providing Soil Moisture Deficits (SMD) don't exceed 40 mm

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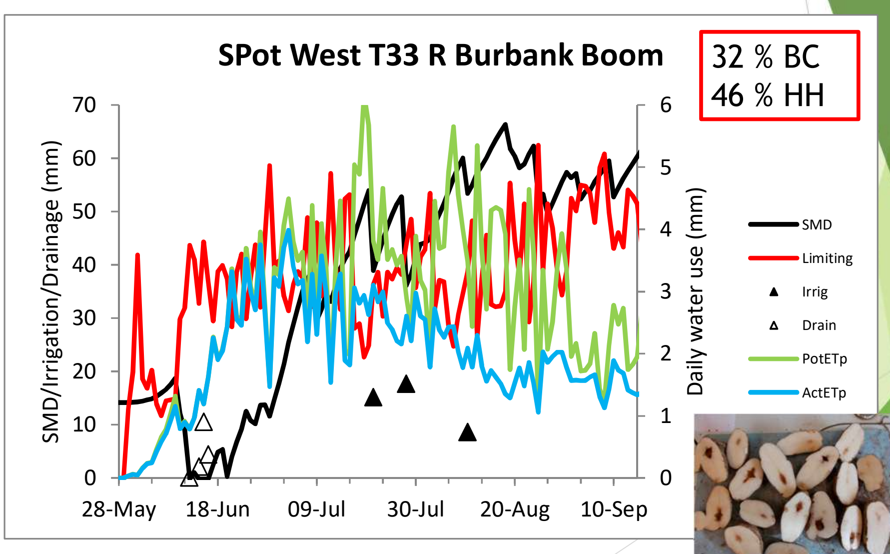
SMD and BC/HH, SPot West 2016



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Fry colour

- No effect on fry colour on free-draining soils

Standard Over-watered

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Recommendations

1. **Varietal scheduling.** Irrigation regimes for scab should be adapted according to varietal susceptibility (higher allowable SMDs for more resistant varieties).
2. **Delayed start irrigation.** For all varieties other than Maris Piper, delaying start of irrigation until 1 week after initial TI would produce equally good control of scab to commencing irrigation at TI. Delayed-start irrigation timing should be based on initial TI as using the date of 50 % TI in variably-emerging fields could lead to more infection.
3. **Duration of irrigation for salad varieties.** A 6-week period for scab control is sufficient in susceptible varieties such as Maris Peer and Charlotte and probably 4-5 weeks in less susceptible varieties such as Regina, Perline or Venezia.
4. **Processing crops.** Where the target is to avoid severe common scab to prevent excessive peeling losses in susceptible varieties, the best time to irrigate is between 1 and 3 weeks after TI, since this coincides with the most rapid phase of pathogen development on tubers. Only irrigating for 2 weeks after TI results in worse common scab than maintaining wet soil for 3 or 4 weeks.
5. **Risk of over-watering.** Over-watering during TI and the scab control phase should be avoided as this increases the incidence of tuber cracking, rotting diseases and internal defects and reduces nitrogen uptake and promotes early senescence
6. **Soil structural conditions.** Growers should not be producing overly-fine seedbeds as this does not improve control of common scab.

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Bruising and irrigation management

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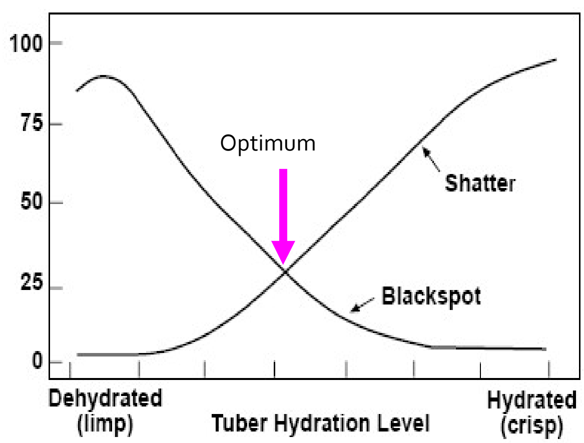
The theory of turgor



Source:
Thornton, Smittle & Petterson (1973)

But they never produced any data to support their hypothesis!

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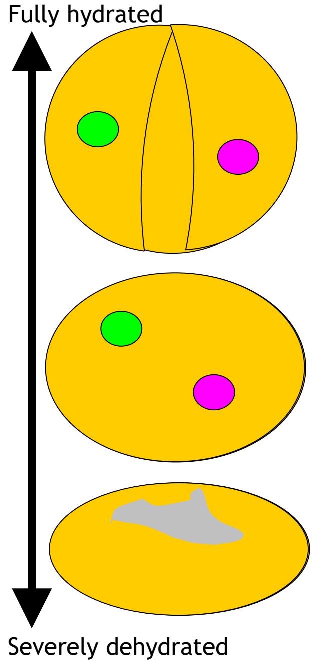

Tissues fully inflated, shock wave transmission very rapid, tissue splits along planes of weakness between cell walls

Tissues partially dehydrated, shock wave dissipates more sideways, cells deform slightly, thereby ‘cushioning’ contents from force

Tissues severely dehydrated, shock wave transmission slow, more lateral spread of energy, internal membranes rupture causing intimate mixing of PPO and tyrosine

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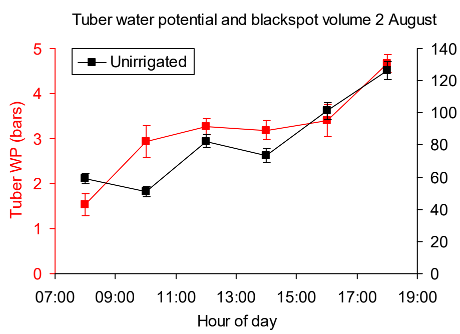
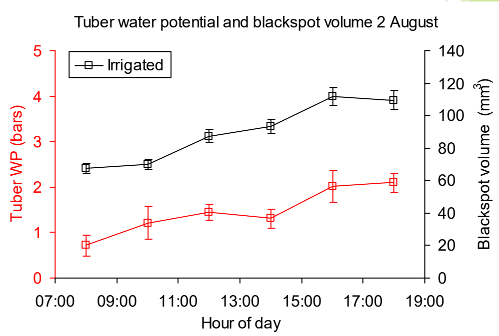
Changes in bruising during the day





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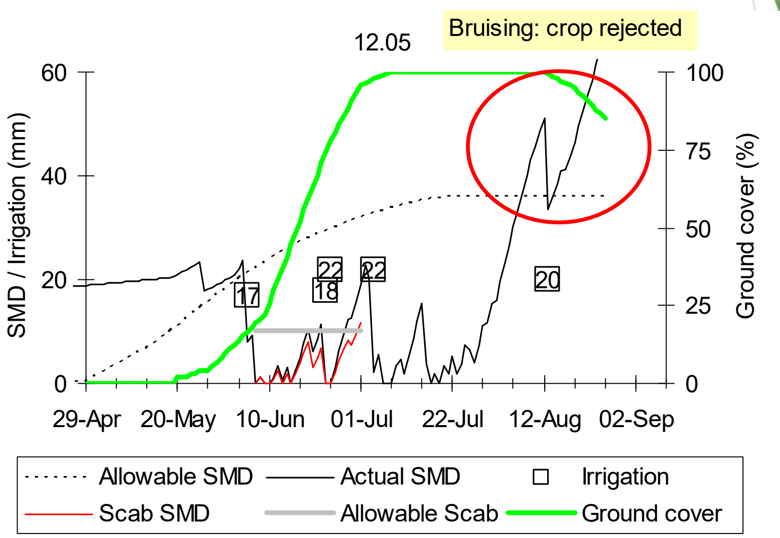
Late-season soil water stress



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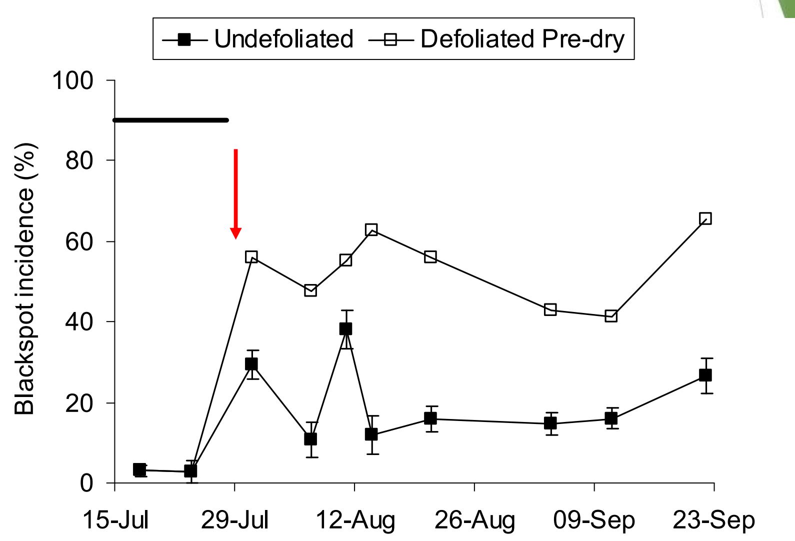
Avoid dry soils at defoliation



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Learning processes ☑

- Water use, evapotranspiration rates, crop coefficients
- Soil water supply (texture, varietal rooting depth, compaction)
- Definitions of soil moisture deficits (critical, limiting, allowable, scab)
- Scheduling methods and practice
- Benefits/disadvantages of soil moisture measurement tools
- Application technology (equipment selection, operation, uniformity)
- Effect of irrigation on crop quality

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