



Sensor-supported irrigation in commercial onion production

An on-farm study in southeastern Sweden

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Sensor-supported irrigation in commercial onion production. An on-farm study in southeastern Sweden

Sensorstödd bevattning i kommersiell lökodling. En fältstudie i sydöstra Sverige

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Abstract

This study examined sensor-supported irrigation management and harvest outcomes in a commercial onion field in southeastern Skåne, Sweden, in 2026. The grower determined irrigation timing and supplied the baseline amount, while soil-sensor graphs and field observations informed recommendations for reduced applications. The non-randomised comparison had two plots per nominal refill treatment. The 100% target was an upper soil-moisture reference; the 80% and 60% targets lay 80% and 60% of the way from a lower irrigation trigger towards that reference, not percentages of applied irrigation. Soil-water-content probes and soil-water-tension sensors recorded local wetting and drying. Irrigation and environmental records supported interpretation. Harvest sampling used four 0.50-m sections per plot of the row of onions formed after lifting.

Across nine events, recorded irrigation totalled 156, 147 and 138 mm for the nominal 100%, 80% and 60% treatments, respectively. The 60% treatment received 18 mm less than the 100% treatment (138 versus 156 mm), an 11.5% reduction. Mean sampled onion mass was 7.7, 7.6 and 7.9 kg per 0.50-m section, including remaining attached foliage and any residual soil. The 60% treatment had more sampled bulbs, lower mean mass per bulb and the smallest mass share above 80 mm. On complete paired days, higher soil-water content was generally associated with lower soil-water tension. Clay content ranged from 4.9% to 15.0% among sampled plots.

Similar sampled masses may reflect adequate water supply and differences in how much water the soils could store. With few plots, different soils and no random allocation of treatments, irrigation effects could not be separated from other field differences. The study shows how soil-sensor information can help guide irrigation within a grower's schedule. Soil, weather and harvest records helped interpret the results. Identifying contrasting soils, monitoring areas prone to water shortage and checking responses across the field could help assess the potential of variable-rate irrigation. Further trials are needed to find suitable irrigation amounts and test whether reductions can be repeated without lowering yield.

Keywords: bulb onion, irrigation scheduling, soil matric potential, volumetric water content, evapotranspiration, on-farm experiment

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Abbreviations

Abbreviation	Meaning
ET	Evapotranspiration
ET ₀	Reference evapotranspiration
ET _c	Crop evapotranspiration
ET _a	Actual evapotranspiration
RF	Unreplicated rainfed reference strip
RMSD	Root mean square paired difference
RTK	Real-time kinematic positioning
SD	Standard deviation
SDG	Sustainable Development Goal
UTC	Coordinated Universal Time
VWC	Volumetric water content

1. Introduction

1.1 Agricultural water management and Swedish relevance

Freshwater scarcity is an important constraint on agricultural production. A global modelling assessment based on 1996-2005 conditions estimated that about four billion people faced severe water scarcity during at least one month of an average year (Mekonnen & Hoekstra 2016). Irrigation can stabilise crop production and reduce exposure to rainfall deficits, but it accounts for the largest share of human freshwater withdrawals (Jägermeyr *et al.* 2017). Expanding irrigation without respecting available water and environmental flow requirements can create conflicts between food production, freshwater ecosystems and other water users. Sustainable irrigation management must therefore match water applications to crop demand while limiting avoidable losses through drainage, runoff and evaporation.

This challenge is also relevant in northern Europe. More than 90% of Swedish agriculture is rainfed and climate projections indicate that dry spring conditions and early-season irrigation requirements may become more frequent even if annual precipitation increases (Grusson *et al.* 2021). In 2023, approximately 146,000 ha, or about 5% of Swedish agricultural land, could be irrigated using the equipment and normal water supply available to farms (Jordbruksverket 2024). The same statistics showed that the area actually irrigated accounted for 2.7% of agricultural land and was concentrated in Götaland; vegetables, potatoes, fruit and berry crops were among the crop groups in which irrigation was most prevalent. These conditions make adaptive water management particularly relevant for high-value vegetable crops whose marketable yield may be affected by short periods of water deficit.

Irrigation management is therefore not simply a question of maximising the amount applied. Applications must be adjusted to crop development, rainfall, atmospheric demand and water already stored in the root zone (Allen *et al.* 1998). This framing is consistent with Sustainable Development Goal (SDG) Target 6.4, which calls for increased water-use efficiency and sustainable freshwater withdrawals (United Nations n.d.-b). It is also consistent with SDG Target 2.4, which calls for productive, sustainable and climate-resilient agricultural practices (United Nations n.d.-a).

1.2 Onion water requirements and deficit irrigation

Onion (*Allium cepa* L.) has a relatively shallow effective root zone: FAO 56 lists a maximum effective rooting-depth range of 0.3-0.6 m for dry onions (Allen *et al.* 1998). Seasonal onion water requirements vary between locations and seasons with different agroclimates (Pérez-Ortolá & Knox 2015). The Food and Agriculture Organization gives an indicative seasonal crop-water requirement of approximately 350-550 mm, while emphasising that such values are only general guides (Brouwer & Heibloem 1986). Consequently, a general crop-water value cannot be transferred directly to a commercial field in southern Sweden without considering local weather, soil properties and crop development.

Onion water demand changes during the season, as documented by lysimeter measurements of evapotranspiration and crop coefficients (López-Urrea *et al.* 2009). Reference evapotranspiration (ET_0) describes atmospheric evaporative demand, whereas crop evapotranspiration under standard, non-water-limited conditions (ET_c) can be estimated using a crop coefficient that changes with crop development (Allen *et al.* 1998). Emergence, transplanting and bulb formation are among the stages most sensitive to water stress (Pérez-Ortolá & Knox 2015). Maintaining progressively drier soil-water-potential thresholds can reduce total yield and the yield of large bulbs (Shock *et al.* 1998; 2000).

Deficit irrigation deliberately applies less than full crop water requirements, either throughout the season or during selected growth stages (Singh *et al.* 2021). Its value depends on whether the saving in applied water is achieved without an unacceptable reduction in yield, marketable bulb-size distribution, quality or crop water productivity. In pooled two-year results from a sweet-onion experiment, yield at 75% ET_c did not differ significantly from yield at 100% ET_c , whereas yield at 50% ET_c was significantly lower than at 100% ET_c (Enciso *et al.* 2009). A non-significant difference does not establish yield equivalence. The nominal percentage must also be distinguished from the realised seasonal irrigation saving.

A nominal irrigation percentage should not be interpreted as proof that the same percentage of plant-available water was maintained in the soil. A root-zone water balance depends on rainfall and irrigation inputs, evapotranspiration, drainage, runoff and changes in soil-water storage (Allen *et al.* 1998). Equal irrigation depths may therefore produce different soil-water responses where texture, organic matter, rooting or initial water content differ. Reduced-irrigation field trials should report the water actually applied and interpret nominal treatments together with measured soil-water dynamics and crop outcomes.

1.3 Irrigation scheduling and soil-water monitoring

Irrigation scheduling can use weather-based estimates of crop demand or measurements of soil-water status, approaches compared experimentally in onion

(Enciso *et al.* 2009). A soil-water balance estimates changes in root-zone storage from rainfall and irrigation inputs, crop evapotranspiration and other gains or losses (Allen *et al.* 1998). In a commercial field, however, effective rainfall, rooting depth, drainage and spatially variable soil properties may not be known precisely. Direct measurements can help reveal local wetting and drying patterns, but their interpretation depends on sensor principle, placement, calibration and data continuity.

Soil-water sensors do not all measure the same quantity. Watermark granular-matrix sensors infer soil matric potential from electrical resistance (Irmak & Haman 2001). Capacitance or frequency-domain probes, including the Sentek Drill & Drop, infer volumetric water content from the dielectric response of the soil surrounding the probe (Campora *et al.* 2020). Matric potential and volumetric water content are related through a soil-water retention relationship, but the conversion is specific to soil type and field location (Varble & Chávez 2011).

Sensor-based scheduling can support water savings, but its performance varies between settings. A systematic review of studies in the United States found generally lower water use with similar or greater yields than grower practices and several weather- or crop-based scheduling approaches, although reported savings varied substantially (Datta & Taghvaeian 2023). Calibration was a major source of sensor error in the same review. A Swiss field comparison of electromagnetic sensors found larger errors in absolute volumetric water content than in temporal anomalies when manufacturer calibrations were used (Mittelbach *et al.* 2012). Sensor response can also depend on soil texture, bulk density, salinity and temperature, as described in that field comparison and in a separate sensor evaluation (Varble & Chávez 2011).

Soil-specific laboratory calibration can improve the agreement of Sentek Drill & Drop readings with reference water contents in sandy materials (Campora *et al.* 2020). Without independent verification, relative wetting and drying at the same location and depth provide a more defensible basis for interpretation than absolute water-content differences between plots.

Measurement scale creates a further limitation. Capacitance profile probes respond to a limited volume of soil around the sensing elements (Paltineanu & Starr 1997; Evett *et al.* 2006). Field studies using granular-matrix sensors have also documented spatial variation that matters for sensor placement and irrigation scheduling (Lo *et al.* 2020b; Hodges *et al.* 2023). Weather-station data and field-scale evapotranspiration estimates provide a different spatial context from measurements beside a soil probe. Combining these observations with farmer experience may help guide irrigation, provided that sensor calibration, spatial coverage and gaps in recording are considered.

1.4 Research problem and study relevance

Applying experimental onion-irrigation strategies in commercial northern-European fields requires attention to both local growing conditions and farm management. Pérez-Ortolá and Knox (2015) reviewed predominantly arid and semi-arid environments and reported that the experimental deficit-irrigation strategies considered had not been adopted commercially at the time of their review. A commercial field offers an opportunity to examine how different irrigation amounts can be applied within an existing production schedule, where protecting the crop is a priority. The practical question is how soil-sensor information can inform adjustments to the grower's usual irrigation and help interpret the resulting crop measurements across a variable field.

The present study evaluated sensor-supported irrigation in a commercial onion field in southeastern Skåne, Sweden. Different irrigation depths were applied by changing the boom travel speed. Three nominal irrigation-refill treatments - 100%, 80% and 60% - were implemented in two field blocks. The percentages represented intended refill levels rather than fixed proportions of each irrigation application. The grower determined when to irrigate and supplied the baseline amount, while soil-sensor graphs and field observations informed recommendations for the reduced treatments. Sentek Drill & Drop profile probes recorded soil-water content at several depths. Watermark granular-matrix sensors reported soil-water tension, indicating how tightly water was held in the soil. The installed CropX Evato system estimated actual evapotranspiration over an area of the field. A nearby Cordulus weather station supplied weather observations and reference evapotranspiration. The environmental records supported retrospective interpretation of the trial.

Alongside Sustainable Development Goal (SDG) Targets 2.4 and 6.4, the study has secondary relevance to efficient resource use under Target 12.2 (United Nations n.d.-c) and adaptive capacity under Target 13.1 (United Nations n.d.-d). These links provide policy context, not evidence of measured progress towards the SDGs.

1.5 Aim and research questions

This study had two aims. The first was to evaluate sensor-supported irrigation under commercial onion-growing conditions by describing the amounts applied to three nominal refill treatments and comparing sampled onion mass, harvested bulb count, pooled mean mass per bulb and bulb-size distribution among them. The second was to assess the information provided by soil-water, weather and evapotranspiration observations for irrigation management and interpretation under spatially heterogeneous field conditions.

Three research questions addressed these aims:

1. What irrigation amounts were applied to the three nominal refill treatments and what soil-water dynamics were observed at the instrumented locations?
2. How did sampled onion mass, harvested bulb count, pooled mean mass per bulb and bulb-size distribution differ among the implemented irrigation treatments?
3. What information did the soil-water, weather and evapotranspiration observations provide for irrigation management and treatment interpretation, given their measurement basis, logging continuity, placement and spatial scale?

2. Materials and Methods

2.1 Study site and crop

The field study was conducted during the 2026 growing season in a commercial onion field near Löderup in southeastern Skåne, Sweden (55.3996° N, 14.1350° E). The project was carried out in collaboration with KARL Irrigation AB. The company develops variable-rate irrigation maps using satellite-derived evapotranspiration data (KARL Irrigation n.d.). The crop was bulb onion (*Allium cepa* L.) cultivar Hyway, sown on 7 April 2026. The repeating bed unit was 1.70 m wide, including the inter-bed working space used for machinery. Each bed contained three bands, each with two onion rows spaced 0.07 m centre-to-centre; band centres were spaced 0.48 m apart. The sowing rate was 41 seeds per linear metre per band, equivalent to 123 seeds per metre of bed before accounting for emergence. The preceding crop was spring barley. Primary tillage consisted of autumn ploughing followed by two spring harrowings.

Before sowing, 800 kg ha⁻¹ of NPK fertiliser with micronutrients (8-5-19) and 600 kg ha⁻¹ of Calciprill were applied. A further 400 kg ha⁻¹ of the same NPK formulation was applied at the one-leaf stage. Calcium nitrate was applied at 130 kg ha⁻¹ on 15 June and 200 kg ha⁻¹ on 20 July.

Environmental and soil-water observations used for the trial-period analyses ended on 18 August 2026. The grower lifted the onions and laid them in windrows on 25 August and harvest sampling was conducted on 31 August.

2.2 Experimental design and plot layout

The implemented experiment was a non-randomised, two-block commercial-field comparison of three nominal irrigation-refill treatments: 100%, 80% and 60%. Each treatment occurred once in Block A and once in Block B. The experimental plots were A3 and B1 for the 100% treatment, A1 and B2 for the 80% treatment and A2 and B3 for the 60% treatment. Block A lay west of Block B (Figure 2.1). From north to south, the physical experimental rows were A3/B3, A2/B2 and A1/B1.

In Block A, the 60% plot A2 and 100% plot A3 were deliberately positioned next to one another because the two available Sentek probes were intended to monitor these treatments in close proximity. Sensors were placed and treatments assigned before the laboratory soil analysis, so measured soil properties were not used to assign treatments. The treatment order was permuted between blocks: A1 was physically parallel to B1, A2 to B2 and A3 to B3, but these parallel plots received different nominal treatments. Irrigation depths were paired across blocks according to treatment rather than physical parallel position: B1 followed A3, B2

followed A1 and B3 followed A2. This arrangement provided a different spatial ordering but did not constitute formal randomisation. The experimental unit for treatment-level agronomic comparisons was the field plot, giving two plots per nominal treatment.

Table 2.1. Implemented treatment and monitoring layout.

Nominal treatment	Block A	Block B	Local soil-water monitoring record	Operational pairing
100% refill	A3	B1	A3: SentekA3 (from 17 June) and WM-25; B1: none	B1 received the A3 depth
80% refill	A1	B2	A1: WM-1; B2: none	B2 received the A1 depth
60% refill	A2	B3	A2: SentekA2 (from 30 June) and WM-17; B3: none	B3 received the A2 depth
Rainfed strip	RF	None	WM-9	No deliberate boom irrigation; descriptive only

Each irrigated treatment plot measured 43 m along the field and 72 m across the irrigation-boom swath, equivalent to 3 096 m². The unreplicated rainfed strip (RF), located farther north on the Block A side, measured 5 × 72 m (360 m²), with the 72-m dimension spanning the boom swath. The main experiment comprised only the six treatment plots A1-A3 and B1-B3; RF was retained as a descriptive reference rather than a replicated treatment.

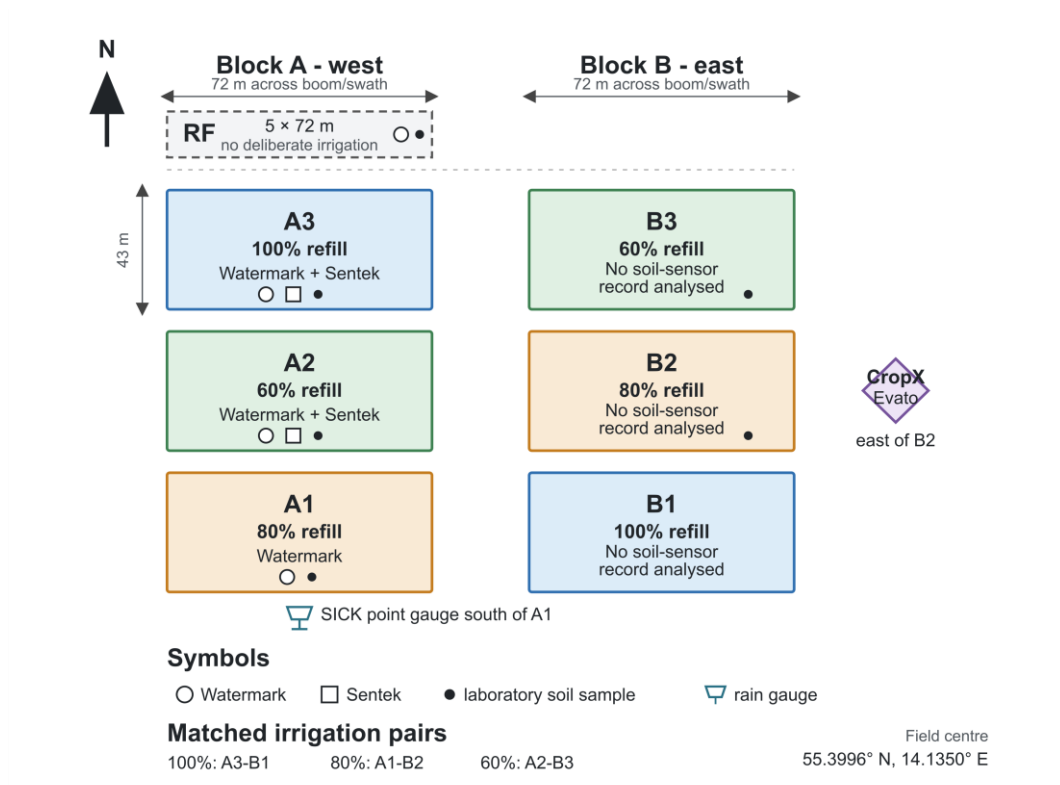


Figure 2.1. Schematic north-up layout of the commercial-field onion irrigation experiment. Block A was west of Block B; from north to south, the physical plot rows were A3/B3, A2/B2 and A1/B1. Each treatment plot measured 43×72 m ($3\,096$ m²) and the unreplicated rainfed reference strip (RF) measured 5×72 m (360 m²). Symbols identify locations represented by the Watermark, Sentek and laboratory soil records used in the analyses. Permanent Sentek probes were installed in A2 and A3 only. B3 was soil sampled (laboratory ID SS_B3), whereas B1 was not. CropX Evato was located east of B2. A SICK tipping-bucket rain gauge was installed in a farmer-managed area south of A1 and received the A3 irrigation schedule. The schematic is not to scale.

2.3 Irrigation treatments and decision process

The nominal treatment percentages described intended post-irrigation soil-water levels within the interval between a lower irrigation-trigger level, termed the refill point, and an upper field-capacity reference. The 100% target was the upper reference; the 80% and 60% targets lay 80% and 60% of the way from the refill point towards that reference. These percentages therefore referred to the refill interval, not to total plant-available water or fixed fractions of the grower's proposed application. The reference levels were used as operational guides, informed by the observed moisture patterns after irrigation, rather than as independently measured soil hydraulic properties. Graphs were assessed relative to the reference levels for each monitored location.

The grower determined the timing and frequency of irrigation and supplied the baseline amount for the nominal 100% treatment. The study worked within this

commercial schedule to investigate reductions without exposing the crop to losses considered unacceptable by the grower. Before each event, recommendations were discussed with the grower using the baseline amount, the available soil-sensor graphs and field observations. The proposed amounts for the reduced treatments considered their observed moisture levels relative to the intended refill targets.

From their respective record starts, the permanent A3 and A2 profiles provided wetting and drying information for the 100% and 60% zones. Visual interpretation focused mainly on the upper 0.40 m, used as a working onion rooting depth rather than a measured root distribution. This visual assessment was distinct from the dashboard's calculated storage summaries. Both Sentek and Watermark information informed the irrigation decision on 14 June, although the earlier Sentek readings were not included in the two permanent-location datasets analysed here. Because A1 (80%) had no permanent Sentek probe, its amount was estimated with reference to the nominal 100% and 60% regimes and the available shallow monitoring and field observations. The same event-level depths were applied to the paired plots in Block B. *Cordulus* evapotranspiration was analysed retrospectively and was not used for irrigation recommendations.

The reference levels and manufacturer-calibrated Sentek readings were used as relative guides. Whether the intended soil-water targets were reached and maintained in each plot was not independently verified. Treatment implementation was therefore described using the recorded irrigation depths and the observed soil-water and harvest measurements.

2.4 Irrigation application and event records

Water was applied using the farm's Rosenqvist irrigation boom (Figure 2.2, right). The grower described the setup as using nozzles labelled 'blue 28' and an R55 end sprinkler. A nominal operating pressure of 1.7 bar was reported by the grower but was not measured during the study. The intended application depth was regulated by changing the boom travel speed. The grower estimated that approximately 4-5 m of travel was required after a speed change before the new speed was reached. This distance was treated as a transition zone at treatment boundaries, not as a quantified error margin for application within the centre of a plot. No tests were conducted to assess how evenly water was applied across the boom or how closely applied amounts matched intended amounts in plot centres. Event dates and irrigation depths were taken from the completed irrigation journal, which contained one record per experimental plot and event.

A SICK tipping-bucket gauge collected rain and sprinkler water at one field location. Water entering the gauge caused its bucket to tip; a connected AgriBox TS1 V2 logging unit recorded the gauge signal used to calculate water totals. The gauge was installed on 30 June 2026 in a farmer-managed plot south of A1. The

gauge was mounted approximately 0.40 m above ground and the surrounding plot received the same event-level irrigation depth as A3 (100%). No field calibration was performed. The cumulative counter was converted to daily totals using Europe/Stockholm calendar dates; a 2.2-mm test-water response recorded during installation was removed from the 30 June total and was not used as a calibration. Because the gauge was exposed to both rainfall and sprinkler water, its daily values represented combined captured water rather than rainfall alone. On irrigation dates, gauge totals were compared descriptively with the recorded A3 irrigation depth and same-day Cordulus rainfall to check whether the records were broadly consistent at that location. The gauge was not a catch-can array and could not quantify boom-wide application uniformity or plot-level application error.

The rainfed reference strip received no deliberate boom irrigation, although minor incidental edge spray could not be excluded. The irrigation journal documented irrigation depths; event-level planned amounts and the reasoning behind each decision were not recorded systematically.

2.5 Soil-water monitoring

2.5.1 Sentek Drill & Drop profile probes

Two Sentek Drill & Drop Bluetooth profile probes were used for permanent monitoring in A3 and A2. The A3 probe was installed on 8 June 2026. The records analysed in this study began on 17 June in A3 and 30 June in A2. Earlier Sentek observations were not combined with the later A3 series because continuity across the record change on 17 June could not be established. The 12 measurement levels were at nominal depths of 5, 15, 25, 35, 45, 55, 65, 75, 85, 95, 105 and 115 cm. The manufacturer lists a 120-cm Bluetooth configuration (Sentek Technologies n.d.-b). For each installation, a vertical borehole was prepared using Sentek-supplied drilling equipment and the probe was inserted according to the manufacturer's guidance (Sentek Technologies n.d.-a).

The A2 record was logged at 15-min intervals after its initial setup readings, while A3 was logged at 30-min intervals. The Drill & Drop Combined Soils calibration configured in IrriMAX was retained and readings are reported as manufacturer-calibrated volumetric water content (VWC). No site-specific calibration was completed. Some irrigation-monitoring graphs displayed readings shifted by a fixed amount. These adjustments were not applied in the analysis. Both records continued into 19 August, but only observations through 18 August were analysed. The Sentek analysis was restricted to A2 and A3.

2.5.2 Watermark granular-matrix sensors

Watermark granular-matrix probes were connected to Niftitech AB Sensmore logging units. These were separate above-ground boxes connected to the buried

probes, recording and transmitting their readings (Figure 2.2, left). The probes reported soil-water tension, the positive magnitude of matric suction, in kPa at nominal depths of 10, 20 and 30 cm. Four logged locations were available: WM-1 in A1 (80%), WM-17 in A2 (60%), WM-25 in A3 (100%) and WM-9 in the rainfed strip. Before installation, the probes were immersed in water in a bag for more than four days. At each location, a set of three probes was installed by excavating a trench approximately 30 cm deep and pushing one probe horizontally into minimally disturbed soil in the crop row at each of 10, 20 and 30 cm depth. All four locations were installed on 8 June 2026. The sensor depth assigned to each logging channel was checked separately for all four units because the channel order differed between devices. No Block B Watermark record was included in the analysis.

Readings recorded before 8 June during pre-installation preparation, including soaking, were excluded from the field analyses. Watermark observations in kPa were retained without conversion to VWC. Data availability was quantified by device and depth and long gaps were not interpolated. Gaps in recording were assessed separately from the plausibility of individual readings because irregular logging does not itself make a reading invalid.

2.6 Weather and evapotranspiration information

Table 2.2. Final trial-period coverage of environmental and soil-water data used in the thesis analyses.

Source	Period in 2026	Measurements and coverage	Analytical role
Sentek	A3: 17 Jun-18 Aug A2: 30 Jun-18 Aug	VWC at 12 depths, 5-115 cm; local profiles in A2 and A3	Within-location profile dynamics; manufacturer calibration
Watermark	8 June-18 Aug	Tension at 10, 20 and 30 cm in A1, A2, A3 and RF	Shallow status; same-day comparison where all depths were observed
CropX Evato	8 Jun-18 Aug	Daily vendor-estimated ET _a over a field area	Field ET comparator; not plot-specific
Cordulus	1 May-18 Aug	Hourly weather and reference ET ₀ ; station 1.15 km north	Nearby weather and rainfall; reference ET for retrospective comparison
SICK gauge	30 Jun-18 Aug	Combined rain and irrigation at one point, 0.40 m above ground	Comparison of collected water with recorded A3 irrigation and Cordulus rainfall
Irrigation journal	14 Jun-8 Aug	Recorded applied depth by plot and event	Implemented irrigation schedules

2.6.1 CropX Evato

A field-installed CropX Evato system (Figure 2.2) supplied daily vendor estimates of actual evapotranspiration (ET_a). The unit was installed according to the supplier's in-field instructions east of B2, beyond Block B. CropX describes Evato as an above-canopy system using direct measurements to estimate field-scale ET_a (CropX Technologies n.d.). The observations were interpreted as information about ET over an area of the field, not as measurements for individual irrigation plots or a fixed 100-m radius.

2.6.2 Cordulus weather data

A Cordulus weather station approximately 1.15 km north of the trial field supplied hourly air temperature, relative humidity, atmospheric pressure, precipitation, wind, radiation and soil-temperature data, together with reference evapotranspiration (ET_0). Analyses used observations from 1 May to 18 August 2026. Timestamps were converted from Coordinated Universal Time (UTC) to Europe/Stockholm time before daily aggregation and event alignment. Weather summaries used the available observations. Cordulus was the primary nearby weather and rainfall record. The specific calculation method was not documented in the study records. Reference ET describes atmospheric evaporative demand for a standard reference surface (Allen *et al.* 1998). It was therefore kept distinct from the actual ET estimated by CropX.



Figure 2.2. Field equipment used in the study. Left: the WM-17 telemetry unit connected to buried Watermark probes. Centre: CropX Evato. Right: the Rosenqvist hose reel and irrigation boom. The monitoring equipment was photographed on 8 June 2026 and the irrigation machinery on 17 June 2026; these are photograph dates, not installation dates.

2.7 Soil sampling and laboratory analysis

Soil samples were collected on 29 June 2026. At each sampled location, a single hole was excavated to 0.30 m and soil from the 0-0.30 m layer was thoroughly homogenised. Approximately 0.5 L of mixed soil was placed in a labelled plastic bag and submitted to Hushållningssällskapet for laboratory analysis. Where local soil sensors were installed, the sampling hole was located within approximately 2 m of the sensor or sensor cluster. Each result therefore represented soil mixed across the sampled depth at one location, rather than soil combined from several independent cores. The results were used descriptively to support local sensor interpretation and characterise field heterogeneity; they were not treated as replicated treatment responses.

The soil analysis included A1, A2, A3, B2 and B3, plus the unreplicated rainfed strip RF. The confirmed matches between laboratory sample IDs and field plots were SS_A1 = RF, SS_A3 = A1, SS_A4 = A2, SS_A5 = A3, SS_B3 = B3 and SS_B4 = B2. B1 was accidentally missed during sampling. Two additional samples from farmer-managed areas outside the trial were excluded. The report included pH, organic matter, particle-size and nutrient analyses, but not bulk density, field capacity, permanent wilting point or a measured retention curve.

2.8 Harvest and agronomic measurements

The grower lifted the onion beds on 25 August 2026 and laid the bulbs above the soil in one windrow per 1.70-m-wide bed. Harvest measurements were made in the field on 31 August, six days after lifting. Four sampling positions were selected in each experimental plot: bottom left (BL), top left (TL), top right (TR) and bottom right (BR). Four additional positions were sampled in RF. The experimental dataset therefore comprised 24 within-plot subsamples and four descriptive RF subsamples (28 harvest samples in total). Positions in the six irrigated plots were reported as approximately 10 m or more inside the outer boundaries to avoid boom-end and speed-transition areas. RF positions were within the 5-m-long strip and therefore could not be 10 m from its ends.

Coordinates were recorded during harvest sampling on 31 August 2026 using a Reach RX2 satellite positioning receiver (Emlid) with real-time kinematic (RTK) corrections. The receiver became available at the trial only on that date and was not used for the initial plot layout, soil sampling or sensor installation. These harvest-day records were not used to reconstruct earlier sampling locations or the pre-lifting ground area represented by the windrow sections.

At each position, a ruler was used to delineate a 0.50-m section along the post-lifting windrow. Where a bulb crossed a sample boundary, it was included when most of the bulb lay inside the section and excluded when most lay outside. This practical boundary rule was necessary because the onions formed a thick,

irregular windrow (Figure 2.3A). Lifting gathered onions from the full bed width into a piled windrow. Movement along the row during lifting was not measured, so the original ground area represented by each 0.50-m section could not be verified.

All bulbs within each segment were included. No rotten bulbs were observed and no defect-based or marketability exclusion was applied. Bulbs were counted and graded in the field using a 3D-printed sizing gauge (Figure 2.3B) with nominal circular apertures of 40, 60, 80 and 90 mm. The gauge was produced using a Bambu Lab A1 mini printer. The 90-mm aperture was not used analytically. A bulb that did not pass through the 80-mm aperture was assigned to the >80 mm class; a bulb that passed 80 mm but not 60 mm was assigned to 60-80 mm; a bulb that passed 60 mm but not 40 mm was assigned to 40-60 mm; and a bulb that passed 40 mm was assigned to <40 mm.

Onions were weighed without deliberately removing the remaining attached foliage; some wilted leaves had detached naturally. They appeared largely free of debris, although residual adhering soil could not be excluded. Weighing used an Alpha Tools electronic hanging scale with a capacity of 50 kg and a retailer-stated accuracy of ± 10 g (Bauhaus n.d.).

Each size class was counted and weighed separately in the field on 31 August. A 260-g bucket tare was subtracted once from every positive recorded class weight; genuinely empty classes remained zero. The four class weights were summed to obtain total net sample mass. The primary harvest outcome was sampled onion mass, defined as the net field-weighed mass of the onions, including remaining attached foliage and any residual adhering soil, in each 0.50-m windrow section. It was not termed yield or marketable yield because no verified ground area or defect-based marketability exclusion was available. Additional measurements were bulb count, pooled mean mass per bulb and size-class mass shares.

For each plot, mean sampled onion mass was calculated as the mean of the four net masses and reported in kg per 0.50-m windrow section. Bulb count was reported on the same sampling basis. Pooled mean mass per bulb was calculated as total sample mass divided by total bulb count across the four sections within each plot.



Figure 2.3. Windrow sampling and the grading gauge. (A) Ruler and tape used to delineate a 0.50-m windrow section during harvest sampling on 31 August 2026 (photograph: Felix Braeuel). (B) The 3D-printed gauge, photographed on 7 September 2026. Classification used the nominal 40-, 60- and 80-mm apertures; the 90-mm aperture was not used.

2.9 Data integration and quality control

Sensor, weather, irrigation, soil and harvest data were organised by plot and date, with measurement depth included where applicable. The A2 and A3 Sentek records contained timestamps, measurement depths and manufacturer-calibrated VWC from IrriMAX. Original measurement values and units were preserved separately from the daily summaries calculated for analysis.

Sentek and Watermark timestamps were recorded in local time. Cordulus timestamps were converted from UTC to local time using the Europe/Stockholm time zone. CropX and SICK records contained dates without times. Data checks

covered duplicate observations, plot and depth assignments, unusual values and gaps in recording. Rainfall and irrigation dates were compared with sensor responses and abrupt changes in the readings were examined visually. Long gaps in sensor records were not filled with estimated values when analysing responses to rainfall and irrigation.

2.10 Statistical and time-series analysis

The plot was the unit of analysis for harvest comparisons. Each of the three nominal irrigation regimes was represented by two plots, one in each block. The four 0.50-m windrow sections sampled within each plot were subsamples, not independent treatment replicates. Because allocation was not randomised and there were only two plots per regime, harvest outcomes were summarised descriptively. The two plot values received equal weight when calculating regime means and between-plot standard deviations. The RF strip was reported separately as one unreplicated reference.

Mean sampled onion mass and mean bulb count per 0.50-m section were calculated by averaging the four section measurements within each plot. Plot-pooled mean mass per bulb was calculated by dividing the total sampled onion mass by the total bulb count across the four sections. Mass shares for the four bulb-size classes were calculated within each plot and then averaged with equal weight across the two plots in each irrigated regime.

Exploratory Pearson correlations were calculated between local clay content and mean sampled onion mass per 0.50-m windrow section across the five irrigated plots with soil analyses. B1 was excluded because no laboratory soil sample was available. The association between mean bulb count per section and plot-pooled mean mass per bulb was examined across all six irrigated plots. The RF strip was excluded from both correlations. These associations were interpreted descriptively because treatment allocation was not randomised and few plots were available. Soil measurements represented one mixed 0-30 cm sample from a specific location within each sampled plot. Bulb count and pooled mean mass were also mathematically related because bulb count was used as the denominator when calculating mean mass per bulb.

Sensor time series were analysed as local observations. Repeated readings from the same monitoring location were not treated as independent treatment replicates. Analyses covered data availability by sensor and depth, wetting and drying patterns and changes around recorded irrigation and rainfall events. Comparisons between the A2 and A3 Sentek records were restricted to their common period from 30 June to 18 August. No Sentek soil-water profile was inferred for A1 or Block B. Watermark availability was summarised using the number and timing of raw kPa observations by device and depth.

Watermark-Sentek correspondence was examined separately in A2 and A3, where both systems were installed. Daily medians were calculated for each measurement depth using local calendar dates. The Watermark shallow-profile summary was the unweighted mean of daily medians at 10, 20 and 30 cm. The Sentek summary was the unweighted mean of daily medians at 5, 15, 25 and 35 cm. Only dates with observations at all specified depths in both systems were included, with no interpolation between dates. Spearman rank correlation was used to describe the association between Watermark kPa and manufacturer-calibrated Sentek VWC. A negative association was expected because increasing Watermark kPa indicates drying, whereas increasing Sentek VWC indicates wetting. This comparison assessed correspondence between the records, not sensor calibration or validation.

Hourly Cordulus reference ET_0 timestamps were converted from UTC to Europe/Stockholm time and hourly amounts were summed by local calendar date. Daily totals were paired with CropX ET_a on matching dates between 8 June and 18 August. Summaries included the number of paired dates, daily means and totals over the paired dates. Daily differences were calculated as CropX minus Cordulus and summarised using the mean difference, mean absolute difference and root mean square difference. Pearson correlation described how actual ET and reference ET varied together. They describe different quantities, so their differences were not interpreted as measurement errors or as a test of accuracy.

A separate retrospective analysis examined the association between evapotranspiration and changes across the full Sentek profile. This analysis was distinct from the upper 0.40 m observations used to guide irrigation. Daily median manufacturer-calibrated VWC was calculated at each of the 12 measurement depths. Each depth was assigned to a 0.10-m layer and a profile water-content index was calculated by summing $VWC/100 \times 100$ mm across the 12 layers. The index therefore represented the 0-1.20 m profile in millimetres of water equivalent. The daily decrease was calculated as the preceding calendar day's index minus the current day's index, with positive values indicating a decrease in recorded water content. The analysis included only pairs of consecutive days with no recorded plot irrigation or Cordulus rainfall on either day. CropX data also had to be available for the second day. Pearson correlations between the daily index decrease and both CropX ET_a and Cordulus ET_0 were calculated separately for A2 and A3. The full-profile index was not an independently calibrated estimate of plant-available water or the measure used to determine irrigation amounts.

The SICK gauge recorded water collected from rainfall and irrigation. For each irrigation date after its installation, the daily gauge total was compared descriptively with the recorded A3 irrigation depth and same-day Cordulus rainfall. The gauge was located outside the six experimental plots in an area managed under the nominal 100% regime. Because it represented only one

collection point and the Cordulus station was approximately 1.15 km away, this comparison was not treated as a formal calibration or a test of irrigation uniformity across the boom.

Data preparation and analytical checks were performed using R and Python scripts. Statistical figures were generated in R using ggplot2, with patchwork used to assemble multi-panel figures. The field layout was prepared as an original vector schematic.

3. Results

3.1 Weather and field-season conditions

Mean air temperature over the observation period was 15.4 °C and observed hourly temperatures ranged from 2.0 to 28.9 °C (Figure 3.1A). The highest temperature, 28.9 °C, occurred on 27 June.

Accumulated Cordulus rainfall from 1 May to 18 August was 116.5 mm. Monthly totals were 41.8 mm in May, 23.8 mm in June, 45.5 mm in July and 5.5 mm from 1 to 18 August. The largest daily total was 16.0 mm on 28 May. During the irrigation-treatment period from 14 June to 8 August, the station recorded 59.3 mm rainfall, while nine irrigation events were applied (Figure 3.1B).

CropX provided 69 daily ET_a observations from 8 June to 18 August. The sum over available days was 285.3 mm, with a daily mean of 4.14 mm and a range of 1.26-6.63 mm. Records were absent for 24-26 July; consequently, the observed sum does not represent a complete 72-day period total (Figure 3.1C). The common environmental and instrument observation period ended on 18 August. The crop was lifted into windrows on 25 August and assessed on 31 August. Additional crop-development dates were not available in the field record.

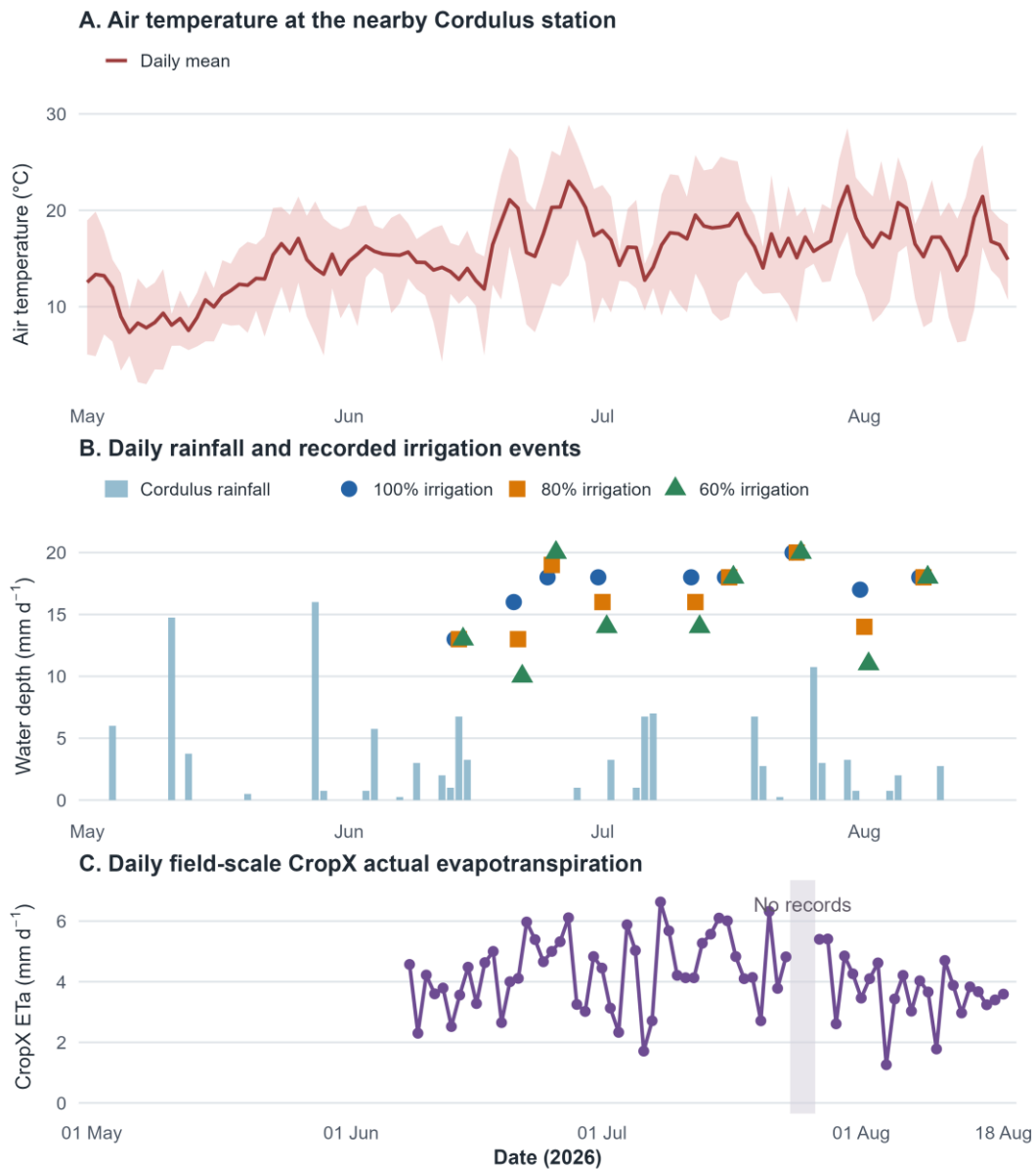


Figure 3.1. Field-season weather, irrigation and evapotranspiration observations. Shading in panel A spans the daily minimum and maximum observed hourly air temperatures. Cordulus temperature and rainfall were aggregated to Europe/Stockholm calendar dates for 1 May-18 August 2026; the station was approximately 1.15 km north of the trial field. Irrigation points show the recorded event-level depths for the nominal 100%, 80% and 60% regimes. CropX ET_a was available from 8 June to 18 August, with no records on 24-26 July.

3.2 Soil characteristics and spatial variation

Laboratory results were available for five of the six experimental plots (A1, A2, A3, B2 and B3) and for the unreplicated rainfed reference (RF). B1 was accidentally missed during sampling. Each value represented one location-specific

sample from the mixed 0-0.30 m soil layer and was therefore used to describe spatial variation rather than as a replicated treatment response (Table 3.1).

Table 3.1. Location-specific pH, organic matter and particle-size results for the experimental plots and rainfed reference. Sand/coarse fraction corresponds to the laboratory field 'Sand and Grovmo'. B1 was not sampled; RF was unreplicated.

Plot	Nominal target	pH	Organic matter (%)	Clay (%)	Sand/coarse (%)	Silt (%)
A3	100%	6.6	4.1	9.9	72	14
B1	100%	-	-	-	-	-
A1	80%	6.7	2.9	4.9	77	15
B2	80%	6.5	3.5	13.0	72	12
A2	60%	7.0	3.6	9.9	72	15
B3	60%	6.8	3.6	15.0	67	14
RF	Rainfed	7.2	2.7	5.3	76	16

Among the five sampled experimental plots, pH ranged from 6.5 to 7.0, organic matter from 2.9% to 4.1%, clay from 4.9% to 15.0%, sand/coarse fraction from 67% to 77% and silt from 12% to 15%. The highest clay contents occurred in the sampled Block B plots B3 (15.0%) and B2 (13.0%). Their same-treatment Block A counterparts, A2 and A1, contained 9.9% and 4.9% clay, respectively. Thus, the sampled plots within the 60% treatment differed by 5.1 percentage points in clay content, while the sampled plots within the 80% treatment differed by 8.1 percentage points. The 100% treatment pair could not be compared because B1 lacked a soil sample.

RF had pH 7.2, 2.7% organic matter and 5.3% clay, with 76% sand/coarse fraction and 16% silt.

3.3 Sensor-data availability

Manufacturer-calibrated Sentek data formed two permanent location-specific records. The analysed A2 record began on 30 June and contained 4,752 complete 12-depth profiles through the 18 August trial endpoint. The A3 record began on 17 June and contained 3,014 complete profiles through 18 August, with a median interval of 30 min. Both plot-specific records contained all 12 depth values at every timestamp. Analysed Sentek coverage was confined to A2 and A3; no record was included for A1 or any Block B plot (Figure 3.2A). Both plot records were analysed as continuous series from their respective start dates.

Raw Watermark matric-potential data were available from 8 June to 18 August at 10, 20 and 30 cm in A1, A2, A3 and RF. The 12 device-depth series contained 60-172 readings each and observations on 36-59 of the 72 calendar days. The

median within-series interval was 6 h for 10 channels and 12 h for two RF channels, but these medians concealed long outages: the largest channel-specific gaps ranged from 4.5 to 29.3 days. Sparse coverage was most pronounced for WM-17 in A2 and WM-9 in RF, although missingness varied among depths and intermittent recovery occurred (Figure 3.2B). The availability summary counted mapped raw kPa records; temporal coverage was evaluated separately from the recorded values. Unequal coverage limits event-by-event comparisons and does not support interpolation across the long gaps.

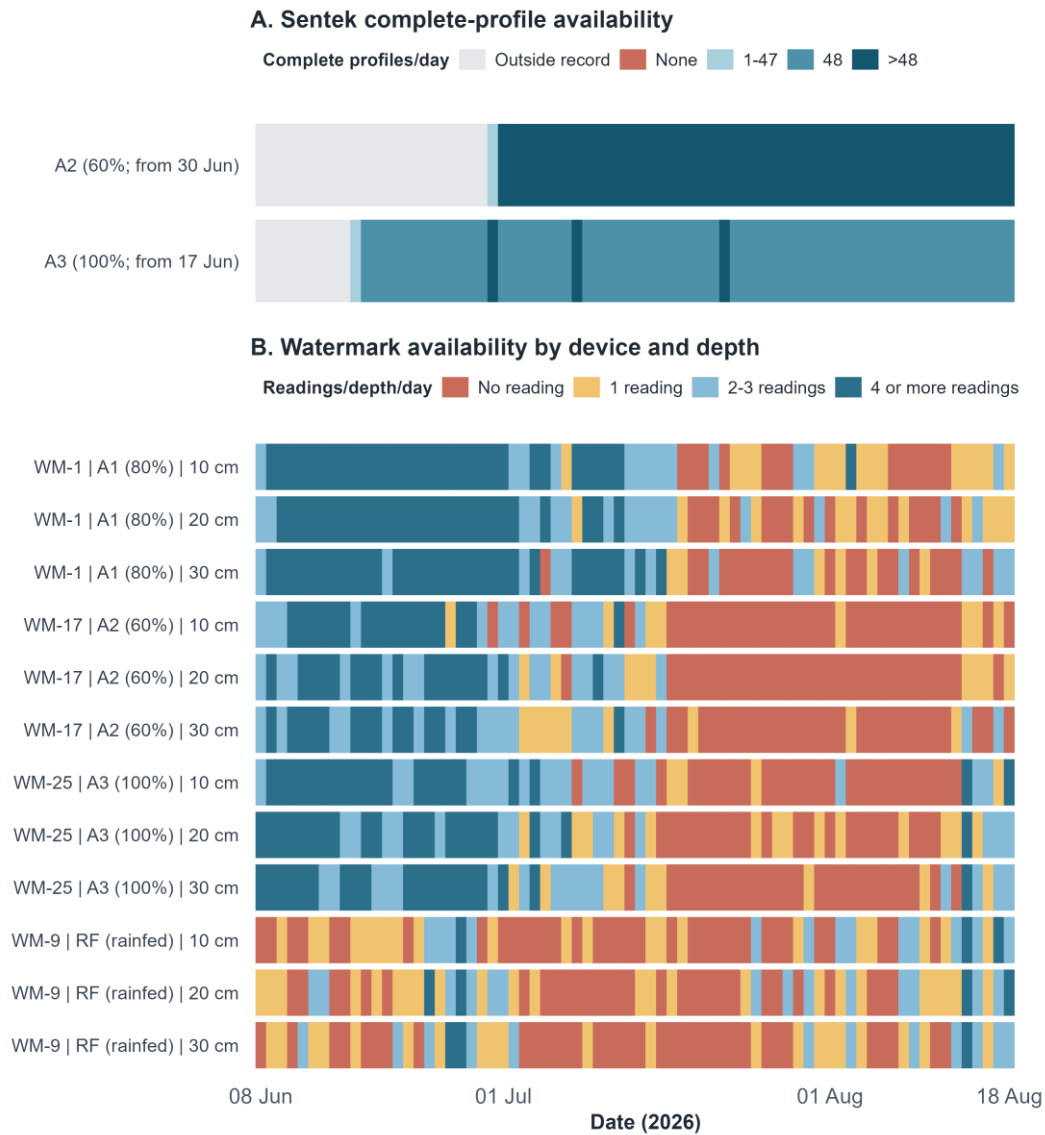


Figure 3.2. Daily availability of raw soil-sensor records from 8 June to 18 August 2026. Sentek colours show complete 12-depth profiles per day; grey denotes dates outside each location-specific record. The plot-specific A2 and A3 records began on 30 June and 17 June, respectively. Watermark colours show the number of raw matric-potential readings per device-depth channel and day. A red cell denotes no observation during the monitored period.

3.4 Applied irrigation and point-gauge comparison

Nine irrigation events were recorded between 14 June and 8 August 2026. Cumulative recorded irrigation was 156 mm in the 100% plots, 147 mm in the 80% plots and 138 mm in the 60% plots. The achieved cumulative inputs in the nominal 80% and 60% treatments were therefore 94.2% and 88.5%, respectively, of the 100% treatment. The total difference between the highest and lowest irrigation input was 18 mm.

The SICK point gauge provided a complete 50-day daily record from 30 June to 18 August after 2.2 mm of installation-test water was removed from the first day. Over this period, the gauge accumulated 187.6 mm. Recorded A3 irrigation totalled 109 mm and nearby Cordulus rainfall totalled 51.0 mm, giving a combined recorded input of 160.0 mm. The gauge total was therefore 27.6 mm (17.2%) higher than the combined record (Figure 3.3A).

Six irrigation events occurred during the gauge period. The gauge accumulated 128.2 mm on those dates, compared with 109 mm in the A3 irrigation record. For the first three events, gauge-minus-recorded differences ranged from -0.4 to +1.2 mm; the later differences were +11.0, +3.0 and +4.6 mm (Figure 3.3B). On the 44 non-irrigation dates, the gauge accumulated 59.4 mm compared with 51.0 mm at the Cordulus station. Because the SICK unit was an uncalibrated single-point gauge, the Cordulus station was approximately 1.15 km away and local rainfall could not be separated from irrigation at the gauge, these differences were treated as a plausibility comparison rather than as estimates of boom accuracy or distribution uniformity.

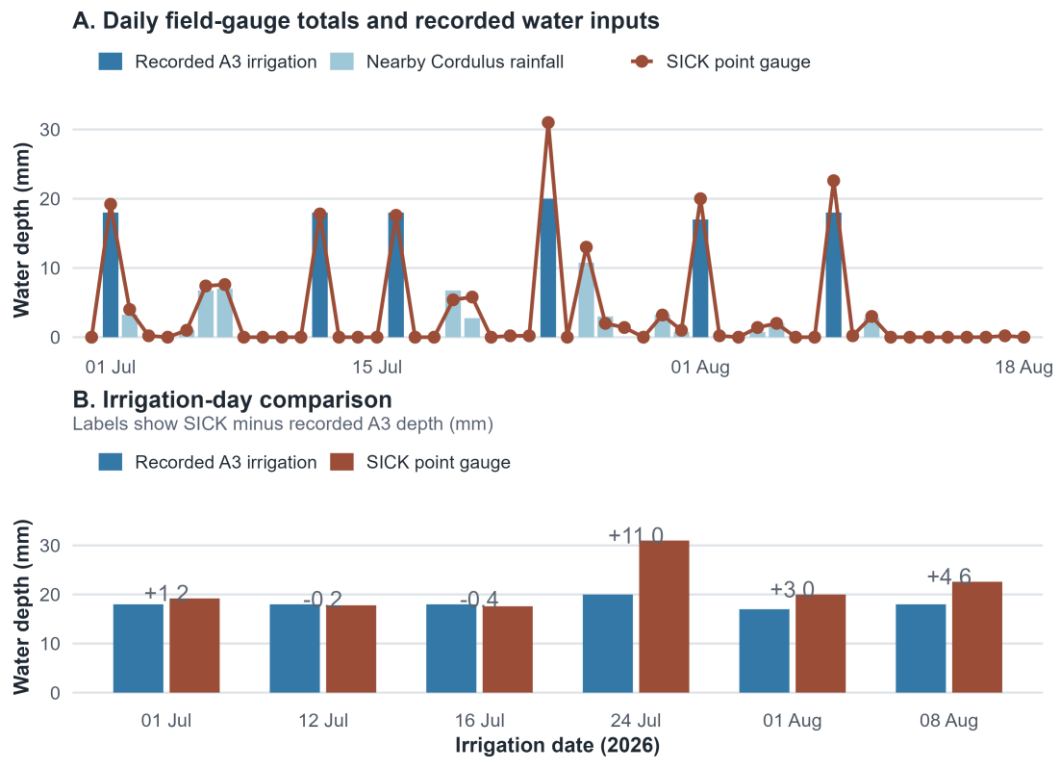


Figure 3.3. Daily SICK point-gauge totals compared with recorded A3 irrigation and nearby Cordulus rainfall from 30 June to 18 August 2026. (A) Stacked bars show recorded A3 irrigation and Cordulus rainfall; points show SICK daily totals. (B) Irrigation-day totals, with labels showing SICK minus recorded A3 depth. Cordulus recorded 0 mm rainfall on all six irrigation dates. The comparison represents one uncalibrated field point and does not test boom-wide distribution uniformity.

3.5 Soil-profile water dynamics

3.5.1 Sentek profile dynamics

Sentek results are reported as manufacturer-calibrated volumetric water content (VWC). No site-specific calibration was completed, so the records were interpreted as relative soil-water dynamics rather than as independently validated absolute VWC. Direct comparison was limited to the single instrumented locations in A2 (60% target) and A3 (100% target); the time series do not constitute replicated treatment measurements.

Both continuing locations had observations on all 50 calendar dates in the common period from 30 June to 18 August. Daily summaries therefore comprised 50 A2 and 50 A3 profiles. During this period A2 received 95 mm irrigation, A3 received 109 mm and the nearby Cordulus station recorded 51.0 mm rainfall. Daily values at each of the 12 depths were summarised by their median. The shallow-profile curve in Figure 3.4C is the unweighted mean of the daily medians at 5, 15, 25 and 35 cm, while the lower-profile curve in Figure 3.4D is the corresponding mean for 45-115 cm.

In A2, the shallow-profile mean ranged from 17.1% to 28.4%, whereas the lower-profile mean ranged from 21.0% to 22.9%. In A3, the shallow-profile mean ranged from 16.6% to 26.8%, whereas the lower-profile mean ranged from 22.5% to 24.1% (Figure 3.4A-D). Absolute level differences between the two probe locations were not used as treatment effects.

Several of the largest shallow-profile increases coincided with recorded water inputs. Across the 20-mm irrigation on 24 July, the shallow-profile means increased by 3.7 percentage points in A2 and 7.9 percentage points in A3 from the preceding to the following day. Following 10.8 mm of rainfall on 26 July and 3.0 mm on 27 July, both shallow profiles reached their highest daily values on 27 July: 28.4% in A2 and 26.8% in A3. Across the final 18-mm irrigation on 8 August, the corresponding increases from the day before to the day after irrigation were 4.3 and 6.8 percentage points. Thereafter, the shallow-profile means declined to 17.1% in A2 and 16.6% in A3 by 18 August. Over the full A3 record, the lower-profile mean declined from 23.9% to 22.5%, while the A2 lower-profile mean declined from 22.8% to 21.0%.

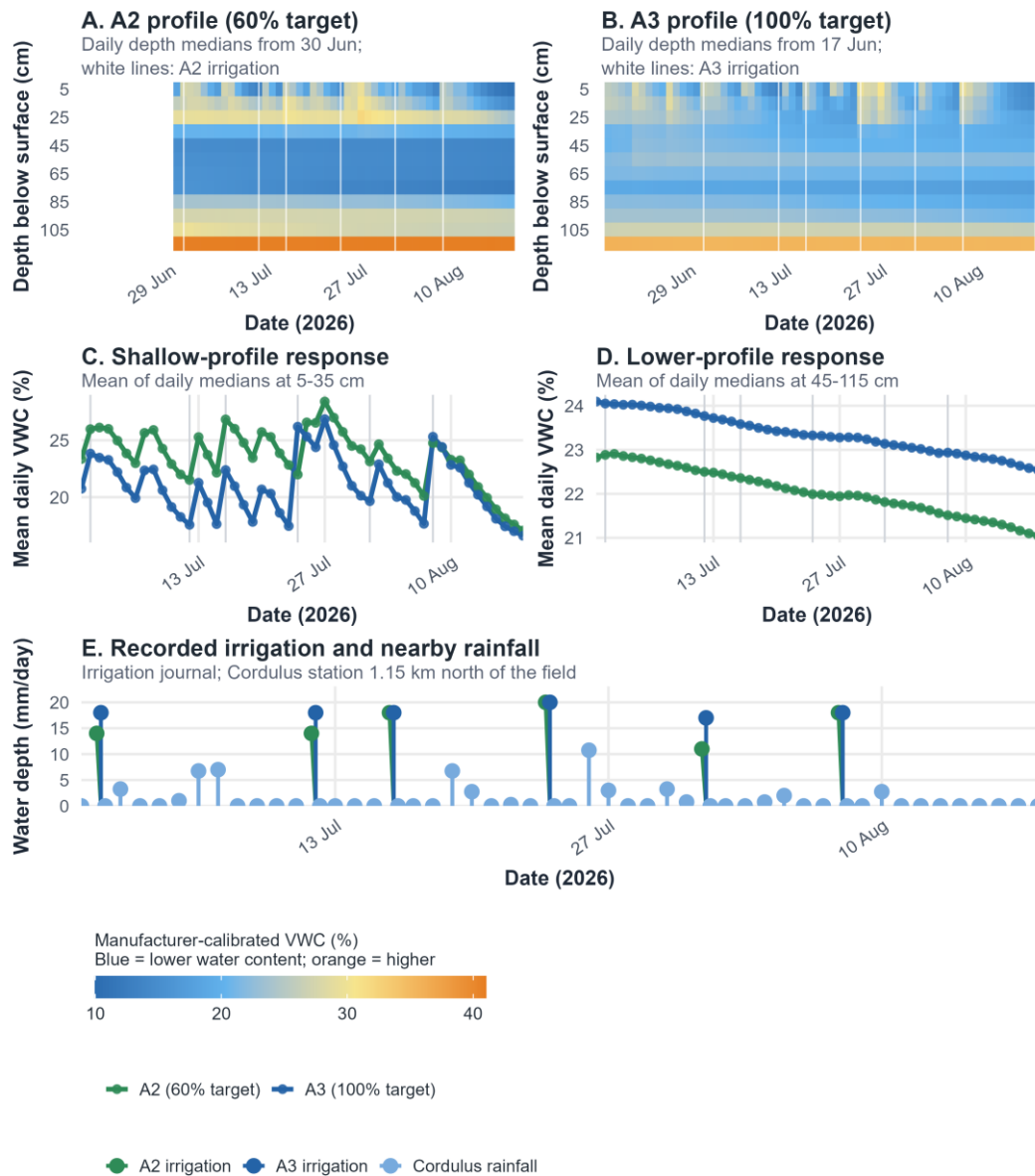


Figure 3.4. Daily manufacturer-calibrated Sentek volumetric water content (VWC), recorded irrigation and nearby rainfall, using Swedish local calendar dates. (A-B) Heatmaps show dates horizontally and nominal sensor depth vertically; colours indicate daily median VWC (%) on the shared scale. White lines mark plot-specific irrigation dates. (C-D) Unweighted means of daily depth medians for the shallow (5-35 cm) and lower (45-115 cm) profiles over the common period. (E) Recorded irrigation and nearby rainfall: A2 and A3 amounts come from the irrigation journal and rainfall from Cordulus, approximately 1.15 km north of the field. Each Sentek plot represents one local probe, without site-specific calibration.

3.5.2 Watermark-Sentek temporal correspondence

At the two plots monitored by both systems, daily shallow-profile Watermark tension and Sentek VWC were inversely associated (Table 3.2). Spearman rank correlations were -0.71 for A2 (12 complete paired days) and -0.89 for A3 (31

complete paired days). Higher Watermark kPa indicates drier soil, whereas higher Sentek VWC indicates wetter soil. Sparse Watermark coverage, particularly in A2, restricted interpretation of individual events; the associations describe temporal correspondence rather than calibration or validation.

Table 3.2. Descriptive Watermark-Sentek correspondence in the two plots monitored by both systems.

Plot	Nominal target	Complete paired days, n	Spearman ρ
A2	60%	12	-0.71
A3	100%	31	-0.89

Daily profiles were unweighted means of depth-specific medians: Watermark at 10, 20 and 30 cm and Sentek at 5, 15, 25 and 35 cm. Only dates with every depth represented were paired, without interpolation. Paired dates spanned 1 July-14 August in A2 and 17 June-18 August in A3. The correlations describe repeated-day association, not calibration, validation or independent treatment replication.

3.6 Evapotranspiration correspondence and profile dry-down

Daily CropX ET_a and Cordulus reference ET_0 were paired on 69 dates from 8 June to 18 August. Mean daily values were 4.14 mm d⁻¹ for CropX and 3.81 mm d⁻¹ for Cordulus. Totals over the 69 dates with data from both systems were 285.3 and 262.9 mm, respectively. CropX exceeded the Cordulus value on 44 of the 69 dates. The mean CropX-minus-Cordulus difference was +0.33 mm d⁻¹, the mean absolute paired difference was 0.72 mm d⁻¹ and the root mean square paired difference was 0.88 mm d⁻¹. The two daily series were positively correlated ($r = 0.72$; Figure 3.5A-B).

Within the common A2-A3 period, 17 pairs of consecutive days per probe met the selection criteria. Neither day had recorded plot irrigation or Cordulus rainfall. CropX data were also available for the second day. CropX ET_a was positively associated with the manufacturer-calibrated Sentek 0-1.20 m profile-depletion index in A2 ($r = 0.57$) and A3 ($r = 0.46$). The corresponding correlations for Cordulus reference ET_0 were 0.81 and 0.73, respectively (Figure 3.5C).

These correlations describe how the measurements varied together on the selected pairs of days. They do not establish instrument accuracy or provide a water balance for either plot. CropX estimated actual ET over a field area, while Cordulus reported reference ET from a station approximately 1.15 km away. Each Sentek record represented one local soil profile using manufacturer calibration. Daily observations were repeated measurements and not independent treatment replicates.

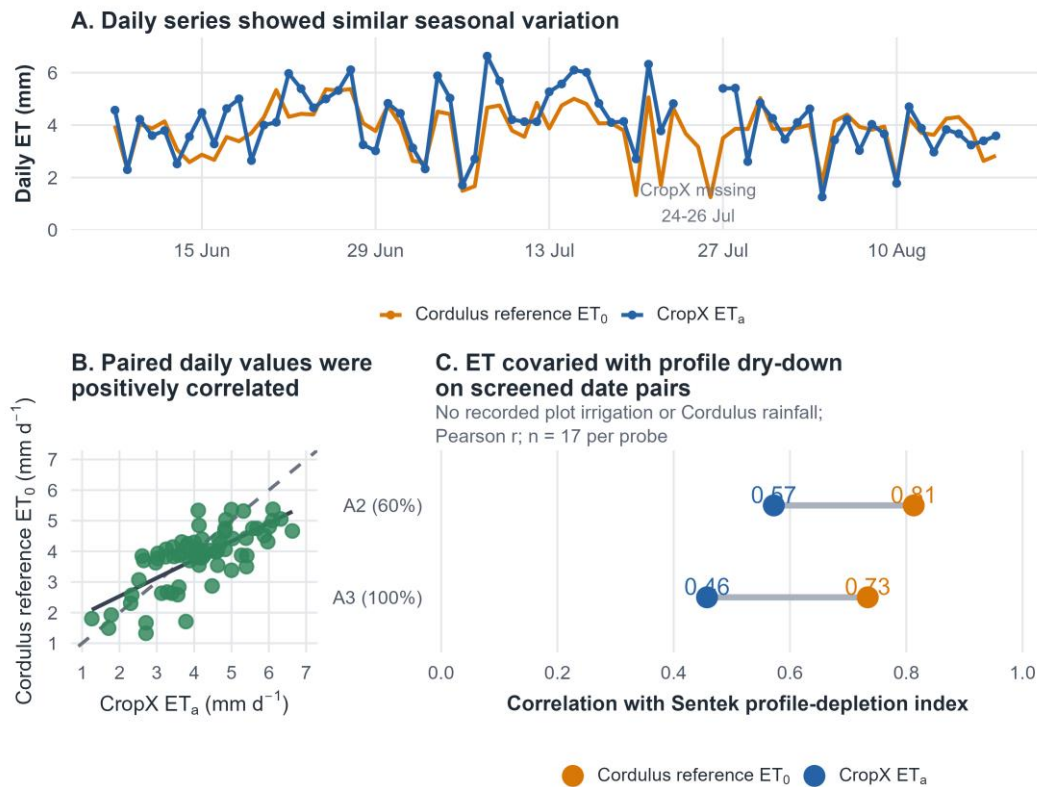


Figure 3.5. Correspondence among daily evapotranspiration records and local soil-profile dry-down. (A) Daily CropX ET_a and Cordulus reference ET_0 from 8 June to 18 August; CropX records were absent on 24-26 July. (B) Paired daily observations ($n = 69$), with the dashed line indicating 1:1 correspondence and the solid line the fitted linear relationship. Pearson r was 0.72. The CropX-minus-Cordulus mean difference, mean absolute paired difference and root mean square paired difference were +0.33, 0.72 and 0.88 mm per day, respectively. (C) Pearson correlations between each ET series and the manufacturer-calibrated Sentek 0-1.20 m profile-depletion index on consecutive date pairs without recorded plot irrigation or Cordulus rainfall ($n = 17$ per probe). Actual and reference ET describe different quantities. These comparisons show correspondence across measurement scales, not instrument validation.

3.7 Harvest measurements

Harvest sampling comprised 24 subsamples from the six experimental plots and four subsamples from the unreplicated RF reference. After tare correction, total sampled onion mass was 198.1 kg, of which 185.0 kg came from the irrigated experimental plots. Each plot estimate was based on four 0.50-m post-lifting windrow sections. All sampled bulbs were included in the mass, count and size-class measurements. Harvest mass is reported in kg per 0.50-m windrow section.

3.7.1 Sampled onion mass

Table 3.3. Recorded irrigation and sampled onion mass per 0.50-m windrow section. For irrigated regimes, mean $\pm$ SD uses two plot means and the range covers eight sections. RF is unreplicated; its mean and range use four sections.

Nominal target	Irrigation (mm)	Block A (kg)	Block B (kg)	Mean $\pm$ SD (kg)	Range (kg)
100%	156	A3: 7.51	B1: 7.84	7.67 $\pm$ 0.23	6.06-8.94
80%	147	A1: 7.14	B2: 7.97	7.55 $\pm$ 0.59	5.74-9.62
60%	138	A2: 7.94	B3: 7.88	7.91 $\pm$ 0.05	6.70-9.32
RF	0	RF: 3.28	-	Unreplicated	3.12-3.44

Mean sampled onion mass was 7.91 kg per 0.50-m windrow section in the 60% treatment, 7.67 kg in the 100% treatment and 7.55 kg in the 80% treatment (Table 3.3). Across the individual irrigated subsamples, sampled onion mass ranged from 5.74 to 9.62 kg. The within-block ranking differed: A2 had the highest plot mean in Block A, whereas B2 had the highest plot mean in Block B. The paired plot means differed by 0.07 kg in the 60% treatment and by 0.83 kg in the 80% treatment. Sampled onion mass did not consistently increase as total recorded irrigation increased (Figure 3.6A).

3.7.2 Harvested bulb count and mean mass

Across the two plots per regime, mean harvest counts were 62.8 bulbs per 0.50-m section in the 60% treatment, 54.6 in the 80% treatment and 57.9 in the 100% treatment. Corresponding pooled mean masses per bulb, calculated within each plot and then averaged across the two plots, were 126.0, 138.1 and 132.6 g bulb⁻¹, respectively (Table 3.4). Thus, the 60% treatment combined the highest sampled bulb count with the lowest mean mass per bulb, whereas the 80% treatment combined the lowest count with the highest mean mass per bulb. These are descriptive summaries from two plots per treatment.

Among individual irrigated plots, mean bulb count ranged from 53.0 in A1 to 63.0 in A2 and plot-pooled mean mass per bulb ranged from 126.0 g in B3 to 141.6 g in B2. The exploratory plot-level association between bulb count and plot-pooled mean mass per bulb was negative ($r = -0.75$, $n = 6$; Figure 3.6C).

Table 3.4. Treatment summaries of harvested bulb count and plot-pooled mean mass per bulb. Values are arithmetic means of the two plot-level values with the between-plot standard deviation (SD). The SD below 0.1 g is reported as such rather than rounded to zero. Mass includes remaining attached foliage and any residual adhering soil. RF is one unreplicated reference, so no standard deviation is shown.

Nominal regime	Plots	Bulb count per 0.50 m, mean $\pm$ SD	Plot-pooled mean mass (g bulb⁻¹), mean $\pm$ SD
100%	A3, B1	57.9 $\pm$ 0.9	132.6 $\pm$ 6.1
80%	A1, B2	54.6 $\pm$ 2.3	138.1 $\pm$ 4.9
60%	A2, B3	62.8 $\pm$ 0.4	126.0 (SD <0.1)
RF	RF	55.3	59.3

3.7.3 Bulb-size distribution

The 60-80 mm class accounted for 75.4% of sampled onion mass in the 60% treatment and 72.7% in both the 80% and 100% treatments. The >80 mm class accounted for 4.2% in the 60% treatment, compared with 12.7% in the 80% treatment and 11.0% in the 100% treatment. The 40-60 mm class represented 19.6%, 13.7% and 15.0% in the 60%, 80% and 100% treatments, respectively. Bulbs <40 mm accounted for 0.9-1.3% of mass in all irrigated treatments.

3.7.4 Unreplicated rainfed reference

The RF reference had a mean sampled onion mass of 3.28 kg per 0.50-m windrow section, which was 57.3% lower than the 7.67-kg mean of the 100% treatment. RF also had the smallest share of mass in the 60-80-mm class and the largest share in the 40-60-mm class (Figure 3.6D). Because RF was unreplicated, it is reported only as a descriptive field reference.

3.7.5 Exploratory soil-harvest relationships

Across the five irrigated plots with laboratory soil data, local clay content and sampled onion mass were positively associated ($r = 0.84$, $n = 5$; Figure 3.6B). This relationship is exploratory because it is based on one depth-mixed, location-specific soil sample per sampled plot, B1 was not sampled, the plots were not randomised and the sample size was small.

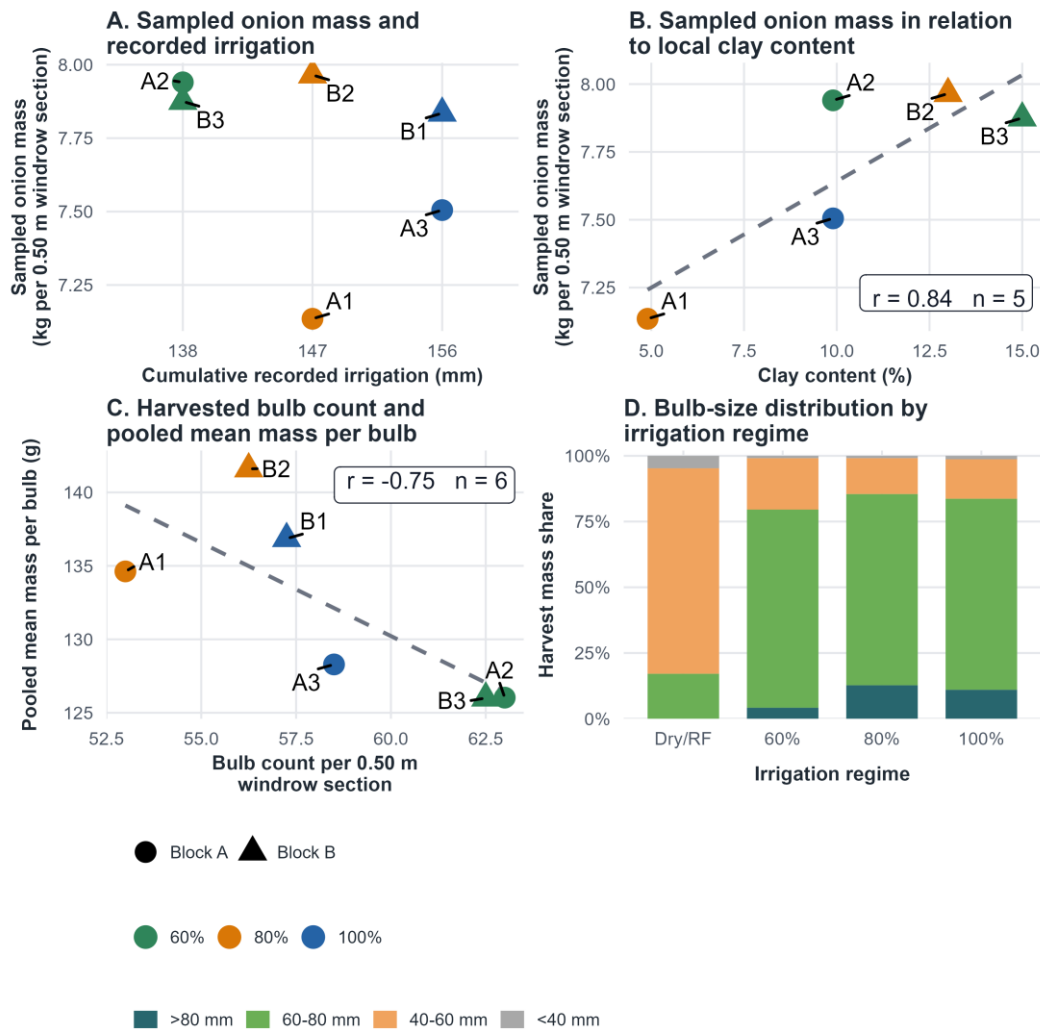


Figure 3.6. Harvest measurements in relation to irrigation, soil and bulb count. (A) Plot-level mean sampled onion mass per 0.50-m post-lifting windrow section versus cumulative recorded irrigation; each point is a separate plot, with colour indicating treatment and shape indicating block. (B) Exploratory clay-mass association for five soil-sampled irrigated plots, with one soil sample per plot; B1 was not sampled. (C) Exploratory relationship between bulb count and pooled mean mass per bulb across the six irrigated plots. These variables are not independent because count is the denominator of mean mass. (D) Mean plot-level mass shares by operational size class; 60-80 mm was the grower's preferred class. Mass includes remaining attached foliage and any residual adhering soil. Irrigated-treatment means give equal weight to two plots; RF is unreplicated.

4. Discussion

4.1 Principal findings under commercial conditions

Sampled onion mass remained within a relatively narrow range despite an 18-mm difference in recorded irrigation, equivalent to an 11.5% reduction from the nominal 100% to the 60% treatment. Across nine events, the treatments received 156, 147 and 138 mm for the nominal 100%, 80% and 60% regimes, respectively. Mean sampled onion masses were 7.7, 7.6 and 7.9 kg per 0.50-m post-lifting windrow section. Sampled mass therefore did not consistently increase with the amount of irrigation recorded.

Bulb count and size distribution added information that the mass totals alone did not show. The 60% treatment combined the highest sampled bulb count with the lowest mean mass per bulb and the smallest mass share above 80 mm. The 60-80 mm class dominated all three irrigated treatments. Similar sampled mass could thus arise from different combinations of bulb number and size.

These outcomes were obtained within the grower's irrigation schedule, not through independently chosen irrigation dates. The grower supplied the baseline amount and recommendations sought to reduce water application while avoiding unacceptable crop losses. The resulting comparison shows how different irrigation amounts were implemented under commercial constraints and what the accompanying soil and harvest observations revealed.

The soil sensors captured local wetting and drying, while the environmental records helped place these responses in context. Soil-water storage and sufficient water supply in all irrigated plots are possible explanations for the small difference in sampled mass. The evidence for these explanations and the practical uses of the monitoring records are considered below; the study's overall limits are brought together in Section 4.6.

4.2 Implemented irrigation contrast and local soil-water response

4.2.1 Nominal targets versus recorded irrigation

The nominal targets described intended soil-water levels, not fixed fractions of the grower's application. As defined in Section 2.3, a 60% target lay 60% of the way from the lower refill point to the field-capacity reference. The amount needed to approach that level depended on how dry the soil appeared before irrigation. A drier plot could therefore receive as much or more water despite having a lower target. On 25 June, for example, the nominal 60% plots received the largest recorded amount because their soil was considered drier. Over the recorded

period, the nominal 80% and 60% treatments received 94.2% and 88.5% of the amount assigned to the 100% treatment. These ratios describe the implemented water reductions, not the soil-water levels achieved.

Both the degree and timing of water limitation matter for onion production. Experiments using soil-water-potential thresholds have demonstrated responses in bulb production (Shock *et al.* 1998), while experiments restricting water at particular growth stages show that treatment timing also matters (Martín de Santa Olalla *et al.* 2004; Pelter *et al.* 2004). Responses also vary between growing environments (Pérez-Ortolá & Knox 2015). A meta-analysis of season-long deficit irrigation across vegetables found that responses varied with crop species, climate, soil texture and production system, although the importance of these factors differed among irrigation levels (Singh *et al.* 2021). The present 18-mm contrast must therefore be interpreted alongside rainfall, soil conditions and the timing of applications.

Cordulus recorded 59.3 mm rainfall during the irrigation-treatment period. Rainfall did not change the arithmetic difference between the irrigation totals, but rain entering the root zone may have reduced water shortage between applications. In a Finnish field study, irrigation increased onion yield in both seasons, although the size of the response differed between years (Suojala *et al.* 1998). This northern-European example shows why an irrigation response observed in one season need not recur to the same extent in another.

Vegetable irrigation scheduling must accommodate farm-management constraints as well as information on soil water and crop demand (Cahn & Johnson 2017). Here, the soil-sensor graphs supplemented the grower's baseline assessment within a schedule that the trial did not control. A2 and A3 had permanent Sentek profiles, A1 relied on field judgement and its shallow Watermark observations and Block B followed the treatment pairings.

4.2.2 Interpretation of the monitored soil profiles

Within the instrumented plots, both Sentek profiles responded to water inputs and subsequently dried between events. Shallow layers showed the clearest short-term fluctuations, whereas the deeper profile varied less over the common observation period. The timing of these changes suggests that the profiles were useful for checking whether soil near the probes became wetter after recorded irrigation or rainfall.

The Sentek graphs were most useful for following changes at the same location and depth. Capacitance-sensor evaluations show that calibration, temperature and the volume of soil sensed can influence inferred water content (Paltineanu & Starr 1997; Schwank *et al.* 2006). Soil-column work has also identified sensor-specific and installation-related limitations (Evelt *et al.* 2006), while a field assessment found appreciable variation among replicate electromagnetic sensors (Lo *et al.*

2020a). These findings support interpreting the A2 and A3 records as local wetting and drying sequences rather than treating their different absolute VWC levels as a treatment effect.

Watermark expanded shallow monitoring to A1 and RF. At A2 and A3, its inverse association with Sentek VWC was consistent with both systems detecting wetting and drying. The comparisons used 12 complete paired days in A2 and 31 in A3, with different periods and measurement depths, so they describe broad temporal correspondence. Logging gaps should not be confused with failure of every recorded measurement. Published studies identify a separate issue: Watermark response has lagged behind tensiometer observations during rapid drying (Thompson *et al.* 2006). A laboratory comparison found slower response than MPS-1 dielectric soil-water-potential sensors above approximately 130 kPa suction (Nolz *et al.* 2013). MPS-1 sensors estimate matric potential from water held in porous ceramic discs; they were comparison instruments in that study, not equipment used here. Such response differences were not independently tested in this trial, and the observed correlations provide neither calibration nor a kPa-to-VWC conversion.

4.3 Harvest response to the implemented irrigation regimes

4.3.1 Sampled onion mass

The ranges of sampled onion mass among individual 0.50-m sections overlapped across the irrigated regimes. The difference between the highest and lowest treatment means was 0.36 kg per 0.50-m section, while differences between the two plots within each treatment were 0.33 kg for the 100% pair (A3 and B1), 0.83 kg for the 80% pair (A1 and B2) and 0.07 kg for the 60% pair (A2 and B3). Variation within the 80% pair was therefore larger than the range among treatment means. This points to the importance of local growing conditions when interpreting the modest differences among regimes.

One possible explanation for the small differences in sampled onion mass is that rainfall, irrigation and stored soil water provided enough water in all three irrigated treatments. Some applications may consequently have exceeded the amount needed to maintain production, but neither crop water stress nor excess irrigation was established here. Onion experiments show that moderate reductions can sometimes maintain similar measured production: Enciso *et al.* (2009) found no significant yield difference between 75% and 100% ET_c in pooled two-year results, whereas 50% ET_c produced less. The effect of an 18-mm contrast would likewise depend on its timing and the soil-water conditions, rather than the seasonal total alone. The present overlapping sampled masses do not demonstrate yield equivalence.

The rainfed reference averaged 3.28 kg per 0.50-m section, 57.3% less than the nominal 100% treatment. It provides useful context for the difference between irrigated and non-irrigated parts of this field. However, RF occupied only one location, so its local soil and growing conditions cannot be separated from the absence of planned irrigation. Possible incidental edge spray adds uncertainty.

4.3.2 Bulb number, mean mass and size distribution

Mean harvested counts were 62.8, 54.6 and 57.9 bulbs per 0.50-m section in the nominal 60%, 80% and 100% treatments, respectively. The corresponding means of plot-pooled mass per bulb were 126.0, 138.1 and 132.6 g. The 60% treatment combined more sampled bulbs with lower mean mass per bulb. Its 60-80 mm mass share was 75.4%, compared with 72.7% in both other irrigated treatments, while its >80 mm share was only 4.2%, compared with 12.7% at 80% and 11.0% at 100%. Its 40-60 mm share was also larger. Irrigation experiments have found changes in grade distribution as well as total production (Martín de Santa Olalla *et al.* 2004; Enciso *et al.* 2009). Onion size-distribution modelling also relates grade composition to mean bulb weight and plant density (de Visser & van den Berg 1998). The present size distributions are therefore worth reporting alongside mass, without attributing them solely to irrigation.

Across the six irrigated plots, harvested bulb count was negatively correlated with pooled mean mass per bulb ($r = -0.75$). Higher planting densities shifted production towards smaller bulb-size classes in field experiments (Rumpel & Felczyński 1997). However, the two variables were also mathematically coupled: pooled mean mass per bulb was calculated as total sampled mass divided by bulb count. A negative association can therefore arise partly from the calculation itself. Without an independent measurement of established plant density, the correlation should not be presented as evidence that denser stands caused smaller bulbs.

The predominance of the grower-preferred 60-80 mm class makes size composition relevant to the commercial interpretation. A smaller oversized fraction could be useful to a grower, but these operational classes and field-weighed samples do not establish a difference in saleable output or income. Future studies could assess these differences using standardised grading and recorded sale prices.

4.4 Soil heterogeneity and spatial interpretation

The irrigation treatments crossed a substantial soil-texture gradient, rather than separating neatly into sandy high-irrigation and finer low-irrigation plots. A2 (60%) and A3 (100%) both contained 9.9% clay. B3 (60%) contained 15.0%, B2 (80%) 13.0% and A1 (80%) 4.9%; B1 (100%) was not sampled. Thus, the greater clay content of B3 may be relevant to its response, but cannot explain the A2-A3 comparison through clay percentage alone. Other measured soil properties and

unmeasured differences in structure, rooting and initial water content may also have mattered.

The relevant soil-water principle is the amount held between field capacity and permanent wilting point over the rooting depth, not clay percentage alone (Allen *et al.* 1998). Figure 4.1 illustrates two hypothetical soils at the same assumed rooting depth. A larger plant-available store can provide a larger buffer before a chosen fraction is depleted. This does not mean that more clay always gives more available water, or that storage alone determines how much irrigation is needed. No retention measurements or complete water balance established whether such a buffer compensated for the 18-mm difference in this trial.

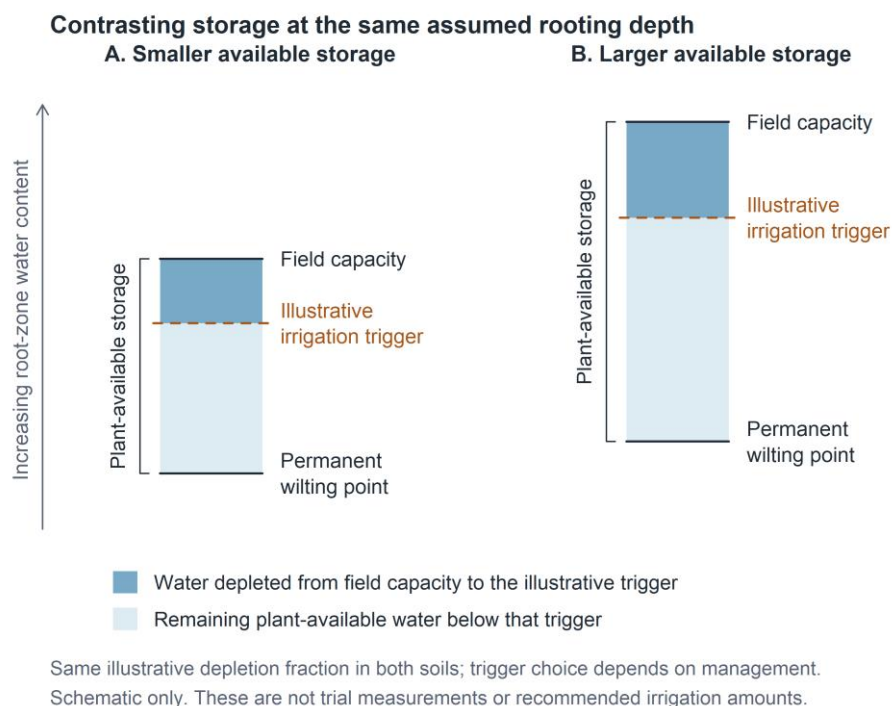


*Figure 4.1. Conceptual comparison of plant-available water storage and irrigation-trigger levels in two hypothetical soils at the same assumed rooting depth. Plant-available storage is the water held between field capacity and permanent wilting point; the trigger is illustrated at the same assumed fraction of depletion from field capacity (Allen *et al.* 1998). The dimensions are schematic, with no numerical soil-water values. The diagram is not a reconstruction of the trial, does not assign storage to particular plots and does not predict irrigation savings or harvest outcomes.*

Across the five soil-sampled irrigated plots, clay content was positively associated with sampled onion mass ($r = 0.84$). This exploratory relationship is compatible with soil conditions contributing to the plot differences, but it does not establish a clay effect. A glasshouse study of spring onion found that soil type modified responses to water limitation (Abbey & Joyce 2004), while modelling of onion irrigation in a humid climate showed that the consequences of uneven application depended on soil and climatic conditions (Pérez-Ortolá *et al.* 2015).

These studies suggest possible explanations, but do not provide a way to adjust this trial's harvest measurements for soil differences.

Soil variation therefore offers one explanation to investigate alongside irrigation amount and harvested bulb count. It does not justify concluding that the reduced regimes maintained sampled mass because all their soils held more available water.

4.5 Practical information value of the monitoring systems

The records were useful for different questions. Soil probes described conditions beside the instruments, environmental records described nearby rainfall and evapotranspiration and the point gauge checked water collected at one field location. Comparing these sources helped interpret both matching patterns and discrepancies.

4.5.1 Sentek and Watermark

Sentek provided high-frequency, depth-resolved observations at two locations. After their respective record starts, the upper 0.40 m readings were the main Sentek information used for visual assessment before irrigation. The full profiles also preserved a detailed record of local wetting and drying responses. Their practical value lay in recognising these changes at the monitored locations, with local soil conditions considered alongside the graphs.

Watermark added shallow matric-potential information, including at locations without a profile probe. Its successfully logged readings retained useful temporal information despite the gaps. Improved logging continuity would make this complementary measurement more useful for short-term scheduling; converting its kPa readings to VWC is not necessary to compare broad wetting and drying patterns.

4.5.2 CropX and Cordulus evapotranspiration

CropX actual ET_a and Cordulus reference ET_0 showed similar temporal behaviour across 69 paired dates ($r = 0.72$), but they were not interchangeable. CropX exceeded Cordulus by 22.4 mm over the paired dates, with a mean daily difference of $+0.33 \text{ mm d}^{-1}$ and RMSD of 0.88 mm d^{-1} . Correlation describes covariation and cannot by itself establish agreement or identify which method is more accurate (Bland & Altman 1986; Legates & McCabe 1999). Here, the comparison concerns different ET quantities, so the mean and root mean square differences are not estimates of instrument error.

The sources also represented different measurement contexts. CropX was installed east of B2 and provided ET_a estimates for an area of the field. The

Cordulus station was approximately 1.15 km north of the field. Cordulus reported reference ET_0 rather than the actual ET estimated by CropX; its specific calculation method was not documented in the study records. Surface-renewal methods use near-canopy temperature fluctuations within a heat-exchange and energy-balance framework (Hu *et al.* 2018). Variable fetch and footprint do not necessarily impair their performance: an evaluation under uniform cotton-field conditions found no consistent relationship between the surface-renewal weighting factor and fetch or footprint (Haymann *et al.* 2019). This general methodological evidence is not product-specific validation of CropX Evato. Without a footprint analysis for this installation, its output should not be assigned to one plot or described as representing a fixed circular radius. Clear identification of the ET variable, time basis, siting and processing is essential when comparing ET information (Allen *et al.* 2011a; 2011b).

Cordulus was more strongly correlated than CropX with the two retrospective Sentek 0-1.20 m profile-depletion series on the 17 date pairs without recorded plot irrigation or Cordulus rainfall. Both ET series therefore contained information related to dry-down, but the result is not an accuracy ranking. Profile change can also include redistribution and possible drainage below the working onion root zone, and local rain may differ from rainfall at the station. The analysis describes correspondence between different measurements, not direct validation of crop water use.

4.5.3 SICK point-gauge comparison

From 30 June to 18 August, the SICK gauge accumulated 187.6 mm, compared with 160.0 mm from recorded A3 irrigation plus Cordulus rainfall. The 27.6-mm discrepancy shows the practical value of retaining an on-field water record alongside the journal and a nearby weather station. Its cause could include differences in local rainfall or irrigation, gauge siting, catch behaviour and the absence of field calibration; it cannot be assigned to irrigation alone.

Application uniformity concerns how irrigation is distributed across an area and cannot be established from one collected total (Zhang *et al.* 2013). Catch-can assessments of variable-rate centre pivots have examined both within-zone distribution and boundaries between application rates (O'Shaughnessy *et al.* 2013). Wind affected absolute catch in that study without appreciably reducing uniformity, whereas solid-set sprinkler experiments showed that wind and operating conditions could change spatial water distribution (Tarjuelo *et al.* 1999). Neither study tested this Rosenqvist boom. The SICK record is therefore a point comparison, not a basis for correcting all plot totals or claiming uniform application across the 72-m boom.

4.5.4 Integrated decision support

For operational recommendations, soil-sensor graphs helped assess local moisture before the grower's scheduled irrigation. For later interpretation, the irrigation journal, soil analyses and harvest samples connected the applied amounts with the observed field responses. CropX, Cordulus and SICK added environmental context and exposed differences between records that would be hidden if only one source were used. The contribution was this combined view of field conditions. Because event-specific reasoning was not recorded systematically and no alternative decision strategy was compared, the study did not measure whether monitoring improved decisions or water-use efficiency.

4.6 Strengths, limitations and scope of evidence

The study's main strength was its examination of sensor-supported irrigation within normal commercial production. The grower controlled irrigation timing and the baseline amount and the trial sought reductions compatible with protecting the crop. Nine event records, local soil measurements and consistent harvest subsampling document what was implemented under those constraints. This gives the findings practical relevance, while defining a narrower question than a controlled search for an optimal irrigation amount.

The comparison covered one site and season, with two non-randomised plots per irrigated regime and one rainfed reference. The four harvest positions within each plot were subsamples, not additional treatment replicates. Different treatment orders in Blocks A and B did not remove potential soil gradients. Simulation work on spatially variable on-farm experiments illustrates why field structure must be considered in both design and analysis (Alesso *et al.* 2019). Here, the design supports describing the observed differences, but not attributing them to irrigation alone.

The recorded irrigation contrast was 18 mm and achievement of the intended soil-water targets was not independently verified. Soil characterisation comprised one mixed 0-0.30 m sample at each sampled location, with no sample from B1; it did not describe within-plot variability or the deeper profile. Dates of emergence, bulb enlargement and top fall were not recorded. It was therefore not possible to link the observed responses to specific crop-development stages. Exploratory correlations based on five or six plots can identify possible explanations, but cannot distinguish their effects.

The monitoring systems also differed in coverage and measurement basis. Two manufacturer-calibrated Sentek profiles could not represent all plots, Watermark gaps restricted event comparisons and the environmental instruments lacked an independent field-wide reference. These constraints limit absolute water-content comparisons, ET accuracy assessment and irrigation verification as specified in

Sections 4.2 and 4.5. They do not remove the information in the valid local records.

Harvest measurements represented short post-lifting windrow sections whose source ground area was not verified. Movement of onions along the row during lifting and the rule for including bulbs that crossed the sample boundary could affect the amount collected from each 0.50-m section. Remaining attached foliage and any residual soil were weighed, without separately quantifying their contributions. Results therefore describe sampled onion mass, count and operational size composition, not trimmed bulb yield per hectare, irrigation water productivity or profitability.

4.7 Practical implications and future research

For Swedish growers using boom and hose-reel systems, the main practical implication is to identify contrasting soil zones before treating one sensor record as representative of a whole field. A location likely to develop water shortage early is a useful monitoring priority. This may be a coarse-textured zone with limited available storage, but soil depth, structure, rooting and initial water status also matter. Responses in other zones should be checked before doses are reduced there.

Variable-rate irrigation (VRI) is worth evaluating where those checks indicate different refill needs. The present comparison suggests a practical sequence: start from the grower's schedule and proposed amount, inspect local wetting and drying records, adjust cautiously where supported and record the applications and crop response. The observed 11.5% reduction in recorded irrigation and relatively small difference in sampled mass support further investigation. They do not show that the same reduction would preserve yield elsewhere or justify recommending the nominal 60% target.

For scale, the 18-mm difference in recorded irrigation corresponds to 180 m³, or 180,000 litres, per hectare. The Swedish *Gul lök 2025* production budget allows SEK 8,400 per hectare for eight irrigations at SEK 1,050 each (HIR Skåne & Hushållningssällskapet Kalmar Kronoberg Blekinge 2026, pp. 51-52). If each irrigation is assumed to apply 20 mm, the average cost is SEK 5.25/m³. At that average cost, 18 mm corresponds to SEK 945 per hectare. The budget does not specify an irrigation depth, so 20 mm is an illustrative assumption. This calculation does not show the savings achieved in the trial. The budget includes depreciation and interest, which would not necessarily fall when less water is applied. Each irrigated treatment received nine irrigation events. Estimating actual savings would require running-cost records and the additional costs of monitoring and VRI.

A follow-up trial should characterise the soil before placing sensors and allocating treatments. Blocks should be defined using the soil information, with

treatments randomly assigned within each block. More independent plots and multiple seasons would help distinguish management responses from local variation. The required number of plots should be planned using expected field variability and the smallest difference considered agronomically important. Applications should create a measurable contrast while retaining any commercial flexibility being studied, with the reasoning for each event and key crop-development dates documented.

Monitoring should cover contrasting soil zones and replicate profile measurements across treatments. Where absolute water storage is needed, readings should be checked against gravimetric water content, bulk density and soil-water retention measurements. Watermark logging should be checked throughout the season and matric potential retained as a direct variable. A calibrated catch-can array across the boom and speed-transition areas would help verify application depth and distribution. Any ET accuracy study would first need clear variable definitions and an independent reference at a compatible measurement scale.

Using RTK positioning from the start would improve the record of plot boundaries, soil samples, sensors and harvest positions; the receiver was available only at harvest in this study. Checked point identifiers, coordinate-system information and survey-quality records should be retained. For area-based harvest assessment, known bed sections should be marked before lifting or the source area of each windrow section verified. Longer or more numerous samples, consistent foliage and soil removal, commercial grading and reject and price records would permit a stronger assessment of yield, water productivity and economic outcomes.

These priorities retain the trial's commercial focus while making the water reductions and their crop consequences easier to evaluate. They are relevant to the resource-management aims of SDG Targets 2.4, 6.4 and 13.1, without implying that this single trial measured progress towards those targets.

5. Conclusion

The first aim was to describe sensor-supported irrigation and compare harvest outcomes under commercial conditions. For research question 1, nine recorded irrigation events supplied 156, 147 and 138 mm to the nominal 100%, 80% and 60% treatments, respectively. The lowest total was 18 mm, or 11.5%, below the highest. Recommendations were made within the grower's schedule and baseline assessment. The percentages described intended soil-water refill levels rather than fixed fractions of applied water. At A2 and A3, Sentek recorded shallow wetting after major water inputs and drying between events, with smaller changes deeper in the soil.

For research question 2, mean sampled onion mass was 7.7, 7.6 and 7.9 kg per 0.50-m windrow section in the nominal 100%, 80% and 60% treatments. The 60% treatment combined the highest bulb count with the lowest mean mass per bulb and the smallest mass share above 80 mm. The 80% treatment had the lowest count and highest mean mass per bulb. Bulbs measuring 60-80 mm accounted for most sampled mass in all irrigated treatments. Similar sampled masses therefore contained different numbers and sizes of bulbs. These measurements are not area-based yields and the differences cannot be attributed to irrigation alone.

The second aim and research question 3 concerned the information provided by the monitoring systems. Sentek and Watermark supported interpretation of local wetting and drying, although Watermark logging gaps limited coverage. Nearby weather records and the retrospective ET analysis added context. CropX actual ET and Cordulus reference ET varied together, but represented different quantities and did not establish instrument accuracy. The SICK gauge recorded water collected at one location; its difference from the irrigation journal and nearby rainfall record could not establish how evenly irrigation was distributed across the boom.

The study shows how sensor-supported irrigation can be documented and assessed under commercial farming conditions. For growers, the practical priority is to understand soil variation and check local crop and soil-water responses before adjusting irrigation amounts. The 11.5% reduction in recorded irrigation, accompanied by similar sampled mass, warrants further evaluation. Further trials are needed to identify suitable refill targets and test whether reductions can be repeated without lowering yield. Any financial benefit would also need to be assessed.

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Populärvetenskaplig sammanfattning

Sensorstödd bevattning i ett kommersiellt lökfält

Kan mätningar av markfukten hjälpa lantbrukaren att anpassa bevattningen inom ett lökfält? Det undersöktes under 2026 i ett kommersiellt lökfält nära Löderup i sydöstra Skåne. Vattenmängd och skördeprov jämfördes mellan tre bevattningsmål.

Lantbrukaren bestämde när fältet skulle bevattnas och föreslog vattenmängden. Med hjälp av markgivarnas grafer och observationer i fält föreslogs sedan mindre vattenmängder i delar av fältet. Tre bevattningsmål prövades: 100, 80 och 60 procent, med två försöksrutor för varje mål.

Målen utgick från två nivåer i graferna: en nedre gräns för när bevattning behövdes och en övre referensnivå för markfukten. För att förklara målen kan den nedre gränsen ses som 0 procent och den övre som 100 procent. Målen 80 och 60 procent låg däremellan. Procentsatserna beskrev alltså vilken markfukt man ville nå efter bevattningen. De betydde inte att rutorna skulle få 80 eller 60 procent av lantbrukarens föreslagna vattenmängd.

Fältet bevattnades vid nio tillfällen. Sammanlagt fick rutorna med målen 100, 80 och 60 procent 156, 147 respektive 138 mm vatten. Skillnaden mellan den största och minsta vattenmängden var 18 mm, vilket motsvarar en minskning med 11,5 procent.

Efter att löken hade stränglagts togs fyra prover i varje försöksruta. Varje prov bestod av lökarna från en halv meter av strängen. Lökarna räknades, sorterades efter storlek och vägdes med kvarvarande blast och eventuell jord. Proven vägde i genomsnitt 7,7, 7,6 och 7,9 kg för målen 100, 80 respektive 60 procent. Vid målet 60 procent innehöll proven flest lökar, men medelvikten per lök var lägst. Där utgjorde lökar över 80 mm också en mindre andel av provvikten än vid de andra målen. Lökarna i storleksklassen 60-80 mm stod för den största andelen av provvikten vid alla tre bevattningsmålen. Resultaten räknades inte om till skörd per hektar, eftersom det var osäkert hur stor markyta varje strängprov motsvarade.

Att provvikterna var likartade kan bero på att vattnet räckte till även där bevattningen minskades. Skillnader i jordens förmåga att lagra vatten kan också ha haft betydelse. Lerhalten varierade mellan 4,9 och 15 procent, men två rutor med olika bevattningsmål hade samma lerhalt. Lerhalten ensam visar därför inte hur mycket vatten växterna har tillgång till. Försöket omfattade få rutor och bevattningsmålen hade inte fördelats slumpmässigt mellan dem. Det gick därför inte att avgöra hur mycket av skillnaderna i skördeproven som berodde på bevattningen.

Markgivarna gjorde det möjligt att följa hur jorden blev fuktigare efter bevattning och regn och sedan torkade igen. Luckor i mätningarna begränsade dock vissa jämförelser. Väderuppgifter och uppskattningar av avdunstningen från mark och växter användes för att tolka resultaten i efterhand.

En praktisk lärdom är att undersöka hur jorden varierar inom fältet och följa markfukten där risken för vattenbrist är störst. Innan bevattningen minskas i andra delar behöver även förhållandena där undersökas. Fler försök behövs för att avgöra när mindre bevattning kan användas utan att skörden försämras.

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