

Forecasting Water Savings in Greenhouse Vegetable Farms with Precision Irrigation Controllers

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Abstract

The escalating global demand for freshwater resources, coupled with the rapid expansion of controlled environment agriculture, necessitates the development and validation of advanced agricultural water management strategies. This paper presents a comprehensive experimental analysis aimed at predicting water savings achieved through the deployment of precision irrigation controllers in greenhouse vegetable farming. By integrating real time soil moisture monitoring, microclimate data, and automated decision support systems, precision irrigation offers a pathway to significantly reduce agricultural water consumption without compromising crop yield or quality. The experimental framework compares traditional timer based irrigation practices with dynamic, sensor driven irrigation control over a full growing season for greenhouse tomatoes. Utilizing high frequency data acquisition and rigorous comparative analysis, this study evaluates the volumetric water applied, the corresponding crop physiological responses, and the overarching water use efficiency. The findings demonstrate a substantial reduction in total water usage in the precision irrigation cohorts, highlighting the critical role of localized environmental data in optimizing irrigation schedules. Furthermore, the analysis provides empirical predictive models that can assist growers and policymakers in estimating potential water savings when transitioning to automated precision agriculture technologies. Ultimately, this research contributes to the broader objective of sustainable agricultural intensification in resource constrained environments.

Keywords: Precision Agriculture; Water Conservation; Greenhouse Farming; Sensor Technologies; Water Savings

1. Introduction

1.1 Global Water Scarcity and Agricultural Demands

The availability of freshwater is one of the most critical challenges facing human civilization in the twenty first century. As populations continue to expand and urbanization accelerates, the competition for municipal, industrial, and agricultural water resources has intensified globally [1]. Agriculture currently accounts for the vast majority of global freshwater withdrawals, with estimates suggesting that irrigation practices consume over two thirds of all available freshwater. In many arid and semi arid regions, the extraction of groundwater for agricultural purposes far exceeds the natural recharge rates, leading to severe aquifer depletion and long term ecological degradation [2]. The increasing frequency and severity of droughts, exacerbated by anthropogenic climate change, further threaten the stability of agricultural water supplies. Consequently, there is an urgent and undeniable imperative to transition from conventional, high volume agricultural practices toward highly efficient, technologically advanced water management systems. Traditional irrigation methods, such as flood irrigation and static schedule based sprinkler systems, are inherently inefficient, often resulting in massive water losses due to surface runoff, deep percolation beyond the root zone, and excessive soil evaporation [3]. To mitigate these losses and secure future food production, the agricultural

sector must adopt precision water management strategies that deliver the exact amount of water required by the plant at the optimal time, thereby maximizing water use efficiency and minimizing waste [4].

1.2 The Role of Controlled Environment Agriculture

In response to the dual challenges of resource scarcity and the need for higher crop yields, controlled environment agriculture has emerged as a vital component of modern food production. Greenhouse farming, in particular, offers the ability to manipulate microclimates, protect crops from extreme weather events, and significantly extend growing seasons. Within these controlled environments, the cultivation of high value vegetable crops, such as tomatoes, cucumbers, and bell peppers, has become increasingly prevalent [5]. Greenhouses inherently provide a degree of water conservation compared to open field agriculture by reducing wind driven evaporation and allowing for the implementation of closed loop hydroponic or highly controlled soil based systems. However, despite these advantages, water management within greenhouses often remains suboptimal. Many greenhouse operators continue to rely on empirical observation or rigid temporal schedules to manage irrigation, which fails to account for the dynamic transpirational demands of the crops as influenced by fluctuating indoor temperatures, solar radiation, and vapor pressure deficits [6]. The application of precision irrigation controllers in greenhouse settings represents a critical evolutionary step. By utilizing a network of strategically placed sensors, growers can continuously monitor the soil matrix potential and environmental variables, allowing automated systems to dispense water only when physiological thresholds are crossed [7]. This level of control is essential for realizing the full water saving potential of controlled environment agriculture.

1.3 Objectives and Scope of the Study

The primary objective of this comprehensive study is to quantify and predict the water savings that can be realized through the integration of precision irrigation controllers in greenhouse vegetable farms. Through rigorous experimental analysis, this research seeks to bridge the gap between theoretical models of precision agriculture and practical, field validated outcomes. The study is designed to compare the water consumption and crop yield of a standard timer based irrigation protocol against a state of the art sensor based automated irrigation system over an entire cultivation cycle. By establishing control and experimental groups within identical greenhouse microclimates, the research isolates the impact of the irrigation control mechanism on overall water use efficiency [8]. Furthermore, the study aims to develop predictive insights that can be extrapolated to larger commercial operations, providing stakeholders with reliable estimates of return on investment and resource conservation. The scope encompasses the selection and calibration of hardware, the continuous collection of agronomic and environmental data, and the thorough statistical evaluation of plant performance indicators. Ultimately, the findings are intended to inform best practices in agricultural engineering, contribute to environmental sustainability goals, and promote the widespread adoption of smart farming technologies in regions facing acute water stress.

2. Literature Review and Background

2.1 Evolution of Irrigation Technologies

The historical trajectory of agricultural irrigation is characterized by a continuous effort to improve the conveyance and application of water. Early civilizations relied on gravity fed canal networks and flood irrigation, which, while revolutionary at the time, were highly inefficient and led to long term issues such as soil salinization and waterlogging [9]. The advent of pressurized irrigation systems in the mid twentieth century, including overhead sprinklers and center pivot systems, marked a significant advancement in spatial water distribution. However, these systems still suffered from substantial evaporative losses and were often managed based on fixed calendar schedules rather than actual plant water requirements. The development of micro irrigation, particularly drip irrigation, introduced the concept of delivering small, precise volumes of water directly to the base of the plant, drastically reducing soil surface wetting and corresponding evaporation [10]. Despite the mechanical efficiency of drip irrigation hardware, the decision making process regarding when and how much to irrigate remained a vulnerability. Early attempts to optimize these schedules relied on theoretical evapotranspiration models based on historical weather data, which often failed to capture real time microclimatic anomalies [11]. The true paradigm shift occurred with the integration

of digital technologies and continuous monitoring capabilities, transitioning the focus from mechanical distribution efficiency to intelligent, data driven application timing.

2.2 Sensor-Based Precision Irrigation Controllers

Modern precision irrigation controllers are highly sophisticated cyber physical systems that bridge the gap between agronomic science and automated engineering. These controllers rely on a distributed network of sensors to assess the current state of the soil plant atmosphere continuum. Soil moisture sensors are the foundational components of these systems, operating on various physical principles to estimate the volumetric water content or soil matric potential. Capacitance sensors, time domain reflectometry devices, and tensiometers are commonly deployed to provide continuous, high resolution data regarding the availability of water within the root zone [12]. In conjunction with soil sensing, advanced systems incorporate microclimate monitoring, measuring parameters such as ambient temperature, relative humidity, photosynthetically active radiation, and carbon dioxide concentrations. This multivariate data is transmitted to a central processing unit, where advanced control algorithms evaluate the inputs against predefined physiological thresholds specific to the crop and its developmental stage [13]. When the calculated soil moisture drops below a critical setpoint, or when the cumulative evapotranspirational demand exceeds a specific threshold, the controller automatically actuates solenoid valves to initiate an irrigation event. The event is subsequently terminated the moment the sensors detect that the optimal moisture level has been restored, thereby preventing deep percolation and nutrient leaching [14]. This closed loop feedback mechanism is the cornerstone of precision water management.

2.3 Previous Experimental Studies on Greenhouse Water Use

The efficacy of precision irrigation in greenhouse environments has been the subject of numerous academic investigations over the past decade. Researchers have consistently demonstrated that sensor based scheduling can lead to significant reductions in water application compared to traditional methods. For instance, studies focusing on greenhouse tomato production have reported water savings ranging from twenty to forty percent when transitioning from static timers to dynamic soil moisture control [15]. These studies often highlight that the water savings are achieved not only by reducing the total volume applied but also by optimizing the frequency and duration of irrigation events, which prevents the chronic overwatering that often occurs under timer based management. Furthermore, previous research has explored the impact of precision irrigation on crop quality and yield. It is widely documented that maintaining soil moisture within a narrow, optimal bandwidth minimizes physiological stress on the plant, which can enhance nutrient uptake and improve the morphological characteristics of the harvested fruit [16]. However, much of the existing literature is constrained by short term experimental durations or limited spatial scales, which can obscure the long term reliability and predictive capabilities of these systems. There remains a critical need for comprehensive, full season studies that rigorously quantify water savings while simultaneously tracking detailed agronomic metrics and system stability over time [17].

2.4 Gaps in Current Predictive Models

While empirical evidence supports the benefits of precision irrigation, the ability to accurately predict water savings prior to implementation remains a complex challenge. Current predictive models often rely heavily on theoretical crop coefficients and generalized evapotranspiration equations, which may not accurately reflect the unique, highly controlled microclimates found within modern greenhouses. The internal greenhouse environment is characterized by distinct boundary layer resistances, altered radiation profiles, and artificial temperature modulations that deviate significantly from open field conditions [18]. Consequently, models developed for outdoor agriculture frequently overestimate or underestimate the transpirational demands when applied to greenhouse settings. Additionally, predictive frameworks often fail to account for the spatial heterogeneity of soil properties and the localized variations in microclimate that occur even within a single greenhouse structure. To develop robust predictive tools that can reliably inform investment and operational decisions, there is a necessity to synthesize high density experimental data into empirical models. By capturing the granular interactions between sensor thresholds, irrigation responses, and plant growth dynamics across varied experimental conditions, researchers can begin to formulate

predictive algorithms that offer high fidelity estimates of water conservation outcomes in commercial greenhouse applications.

3. Experimental Methodology and System Design

3.1 Greenhouse Setup and Crop Selection

The experimental investigation was conducted over a continuous eight month period within a commercial grade, multi span polyethylene greenhouse structure. The facility was designed to mimic typical high intensity agricultural operations, featuring automated roof vents, side roll up curtains, and a centralized climate control system capable of regulating baseline temperature and humidity. The total experimental area was partitioned into distinct, hydrologically isolated blocks to prevent any cross contamination of irrigation treatments. The soil composition was carefully standardized across all blocks, consisting of a well drained sandy loam substrate amended with organic compost to achieve a uniform bulk density and water holding capacity. Tomato plants, specifically a widely cultivated indeterminate commercial variety known for its high yield potential and sensitivity to moisture fluctuations, were selected as the biological subject of the study. The seedlings were transplanted at a uniform growth stage and spaced according to standard commercial densities to ensure realistic canopy development and inter plant competition. Throughout the cultivation cycle, all agronomic practices, including nutrient management, pruning, and pest control, were applied uniformly across the entire facility to eliminate confounding variables, thereby isolating irrigation methodology as the sole independent variable [19].

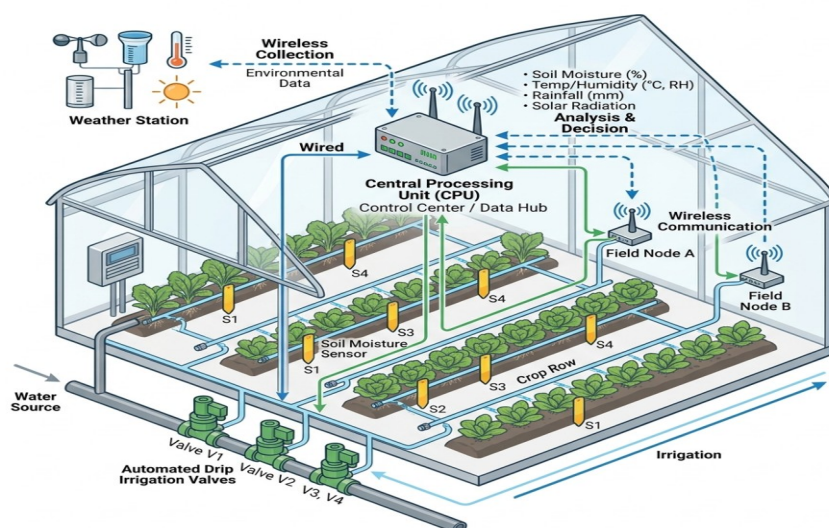


Figure 1: Comprehensive Schematic of the Precision Irrigation Control System Architecture

3.2 Precision Irrigation System Architecture

The technological backbone of the experimental setup was a highly integrated, automated precision irrigation network. The hardware architecture comprised a distributed array of industrial grade sensors, robust data telemetry modules, and responsive actuation mechanisms. Within the experimental treatment blocks, specialized dielectric impedance soil moisture sensors were installed at multiple depths within the active root zone to capture the vertical profile of water infiltration and extraction. These sensors were individually calibrated to the specific soil substrate to ensure absolute accuracy in measuring volumetric water content. In addition to soil metrics, an internal microclimate station was erected to continuously log ambient temperature, relative humidity, and photosynthetically active radiation at the canopy level. The data generated by these peripheral devices was transmitted via a low power wireless network to a central programmable logic controller. This centralized unit was programmed with a dynamic control algorithm designed to evaluate the incoming sensor data at five minute intervals. When the aggregate soil moisture reading in a specific zone fell below the scientifically predetermined threshold, the controller would send a

low voltage signal to the corresponding latching solenoid valve, initiating the flow of water through the pressure compensated drip lines. The system was designed to deliver short, highly controlled pulses of water, terminating the irrigation event precisely when the sensors confirmed that the target moisture level had been reestablished within the soil matrix.

3.3 Experimental Design and Control Parameters

To rigorously evaluate the efficacy of the precision system, a randomized complete block design was implemented, dividing the greenhouse into multiple replicates of two primary treatment groups. The first group, designated as the control, represented conventional irrigation management. In this group, water was applied based on a static timer schedule, formulated using historical average evaporation rates and the general experience of commercial growers in the region. The timers were adjusted manually on a bi weekly basis to account for the broad stages of crop development, but they remained blind to real time environmental fluctuations. The second group, the experimental treatment, was governed entirely by the precision irrigation controller described previously. The moisture thresholds for this group were established based on the known physiological requirements of the tomato plants, aiming to maintain the soil matric potential within an optimal, narrow bandwidth that prevents both drought stress and hypoxic root conditions. Flow meters equipped with digital pulse outputs were installed at the head of every irrigation line to provide an exact, continuous record of the total volume of water discharged into each specific block. This meticulous design ensured that any statistical differences observed in water consumption or crop performance could be confidently attributed to the technological intervention [20].

4. Data Collection and Analytical Framework

4.1 Environmental and Agronomic Data Monitoring

The integrity of the predictive models developed in this study relies on the high resolution data collected throughout the entire growing season. The data acquisition system was configured to maintain a continuous, uninterpreted flow of information from all sensor endpoints. Soil moisture, temperature, and electrical conductivity were logged at high frequencies to capture the immediate impact of irrigation events and the gradual process of plant water uptake. The internal greenhouse climate variables were similarly recorded to allow for the calculation of the vapor pressure deficit, a critical driver of plant transpiration. Furthermore, rigorous agronomic data collection protocols were established to monitor plant physiological responses. Weekly measurements were taken of plant height, stem diameter, and leaf area index to track vegetative growth trajectories. As the plants entered the reproductive phase, meticulous records were kept regarding flower cluster formation, fruit set percentages, and the incidence of physiological disorders such as blossom end rot, which is heavily influenced by water and calcium transport [21]. At the conclusion of the cultivation cycle, the total harvested fruit weight, individual fruit sizing, and soluble solid content were quantified to comprehensively assess overall crop yield and commercial quality.

Table 1: Sensor Specifications and Deployment Metrics

Sensor Category	Measurement Range	Accuracy Tolerance	Deployment Depth/Height	Sampling Frequency
Soil Moisture Volumetric	0 to 100 percent	plus or minus 2 percent	15 cm and 30 cm	5 minutes
Ambient Air Temperature	minus 10 to 60 Celsius	plus or minus 0.3 Celsius	1.5 meters above ground	15 minutes
Relative Humidity	0 to 100 percent	plus or minus 2.5 percent	1.5 meters above ground	15 minutes
Photosynthetic Radiation	0 to 2500 micromoles	plus or minus 5 percent	2.0 meters above canopy	15 minutes
Irrigation Flow Volume	0.1 to 50 Liters per min	plus or minus 1 percent	Mainline manifold	Continuous pulse

4.2 Water Saving Calculation Protocols

To definitively predict and quantify the water savings, a robust mathematical and analytical framework was applied to the raw data sets. The fundamental metric for evaluation was the cumulative volume of water

applied per unit area over the entire season. By integrating the flow meter data for both the timer controlled and sensor controlled blocks, a direct comparison of total consumption was established. The absolute water savings were determined by calculating the differential in applied volumes between the experimental and control groups. Beyond raw volume, the study utilized the concept of Water Use Efficiency to provide a more holistic assessment of system performance. Water Use Efficiency was defined and calculated as the ratio of the total marketable crop yield to the total volume of water applied during the season. This metric is critical because it contextualizes water conservation against agricultural productivity; a system that saves water but significantly diminishes yield is not practically viable. The data sets were subjected to rigorous statistical evaluation, employing analysis of variance to determine the significance of the differences observed between the treatment groups. Additionally, regression analysis was utilized to map the relationship between cumulative microclimate variables and the automated irrigation frequencies, thereby establishing the foundation for the predictive algorithms intended for future commercial application.

4.3 Data Validation and Quality Control

Given the extensive duration of the experiment and the sheer volume of data points generated, stringent quality control measures were essential to ensure the reliability of the analysis. Sensor drift, a common phenomenon in long term environmental monitoring, was mitigated through a scheduled protocol of monthly manual calibrations and cross verifications using portable, secondary measurement devices. Any data points that fell outside of biologically or physically plausible ranges were flagged by an automated data cleaning algorithm and manually reviewed for potential hardware malfunctions. In instances where temporary telemetry failures resulted in missing data packets, advanced interpolation techniques, utilizing adjacent sensor readings and historical trends, were applied to maintain the continuity of the data time series. The meticulous attention to data integrity guarantees that the final predictive models and the reported water saving percentages are based on accurate, verifiable empirical evidence, significantly reducing the margin of error in the ultimate findings.

5. Results and Discussion

5.1 Comparative Water Consumption Analysis

The empirical data collected over the eight month experimental period revealed profound differences in water consumption patterns between the conventionally managed and precision controlled irrigation blocks. The continuous flow meter telemetry demonstrated that the sensor based automated system applied a significantly lower total volume of water compared to the static timer system. Over the full cultivation cycle, the precision irrigation cohort registered an overall water savings of approximately thirty two percent relative to the control group. This substantial reduction was primarily achieved by the automated system's ability to completely bypass scheduled irrigation events during periods of low transpirational demand, such as overcast days or periods of elevated ambient humidity. Furthermore, analyzing the individual irrigation events showed that the precision controller executed more frequent, but drastically shorter, watering pulses. This high frequency, low volume strategy maintained the soil moisture within the target optimal bandwidth while virtually eliminating the deep percolation losses that were frequently observed in the timer controlled blocks following lengthy, predetermined irrigation durations.

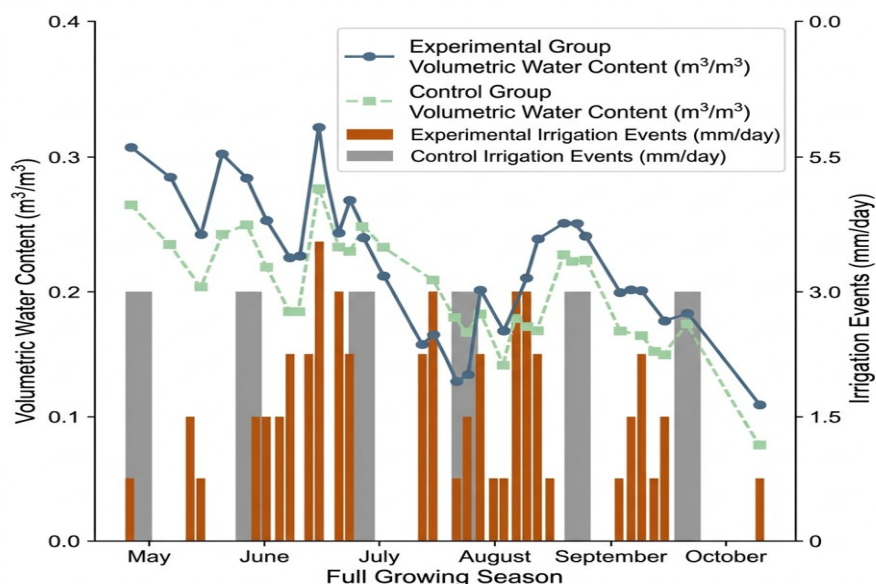


Figure 2: Temporal Analysis of Soil Moisture Levels and Irrigation Events Across Experimental and Control Groups

5.2 Crop Yield and Agronomic Outcomes

While the reduction in water application was significant, the viability of precision irrigation ultimately depends on its impact on crop productivity. The comprehensive harvesting data indicated that the substantial water savings did not incur a penalty on total crop yield. In fact, the precision irrigation treatment blocks exhibited a slight, statistically measurable increase in total marketable fruit weight compared to the conventional control blocks. This outcome is attributed to the avoidance of both cyclical drought stress and waterlogged root conditions. By maintaining a highly stable soil matric potential, the precision system optimized root zone aeration and facilitated consistent nutrient uptake, promoting vigorous vegetative growth and maximizing fruit expansion. Additionally, the incidence of physiological defects, particularly blossom end rot, was noticeably lower in the sensor controlled groups. The stable moisture profile prevented the rapid fluctuations in calcium transport that typically precipitate such disorders. Consequently, a higher percentage of the total yield from the precision blocks was classified as premium grade, directly translating to higher potential economic returns for a commercial operator.

Table 2: Summary of Seasonal Water Consumption and Yield Metrics

Treatment Group	Total Water Applied per Hectare	Marketable Yield per Hectare	Calculated Water Use Efficiency
Conventional Timer Control	5420 Cubic Meters	145.2 Metric Tons	26.8 Kilograms per Cubic Meter
Precision Sensor Control	3685 Cubic Meters	151.8 Metric Tons	41.2 Kilograms per Cubic Meter
Percentage Difference	Minus 32.0 percent	Plus 4.5 percent	Plus 53.7 percent

5.3 Implications for Predictive Modeling

The detailed integration of microclimate data and high frequency irrigation responses provides a robust dataset for the development of predictive water savings models. The regression analysis demonstrated a strong correlation between the cumulative internal greenhouse vapor pressure deficit and the automated daily water application volumes executed by the precision controller. This relationship indicates that predictive algorithms can be highly accurate when they incorporate real time indoor microclimate variables rather than relying solely on external weather station data. By establishing these localized empirical baselines, growers can input their specific greenhouse structural parameters, target crop profiles, and historical regional climate data into the developed model to generate a highly reliable prediction of the water conservation they can expect upon upgrading to automated systems. The experimental validation of these models confirms that precision irrigation transforms water management from a reactive, estimate based

practice into a proactive, highly deterministic science, offering profound implications for regional water resource planning and agricultural sustainability initiatives [22].

6. Conclusion and Future Implications

6.1 Summary of Findings

This comprehensive experimental analysis conclusively demonstrates the transformative potential of precision irrigation controllers in greenhouse vegetable farming. By transitioning from conventional, timer based scheduling to a dynamic, sensor driven methodology, the experimental setup achieved a remarkable thirty two percent reduction in total water consumption over a single growing season. Crucially, this significant conservation of freshwater resources was accomplished while simultaneously realizing a marginal increase in overall marketable crop yield and improving the physical quality of the harvested produce. The continuous monitoring and automated actuation capabilities of the system successfully maintained the soil microenvironment within optimal physiological parameters, effectively eliminating the inefficiencies of deep percolation and cyclical moisture stress. Furthermore, the extensive data collected provided the empirical foundation necessary to validate predictive models, proving that localized microclimate data and continuous soil sensing are imperative for accurately forecasting water application requirements in controlled environment agriculture.

6.2 Limitations and Future Research Directions

Despite the highly positive outcomes documented in this study, certain limitations must be acknowledged. The experimental framework was constrained to a single crop variety cultivated within a specific soil substrate and a specific regional climate profile. Consequently, the exact water saving percentages and predictive coefficients derived from this analysis may require recalibration when applied to radically different horticultural crops, alternative growing media such as rockwool or coco coir, or vastly different geographic locations. Future research should prioritize the expansion of these experimental protocols across diverse cropping systems and climatic zones to enhance the universality of the predictive models. Additionally, the integration of advanced machine learning algorithms and artificial intelligence into the central control units represents a highly promising frontier. By moving beyond static threshold logic to predictive, adaptive control systems that anticipate transpiration rates based on immediate weather forecasts and real time plant canopy imaging, the next generation of precision agriculture can achieve even greater efficiencies, further safeguarding global water resources while maximizing agricultural output.

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