

PROTOCOL FOR THE EVALUATION OF THE EFFECTIVENESS OF EACH GROWING CYCLE AND PROCESS FROM A QUALITATIVE POINT OF VIEW

*A laboratory-scale validation of the Gardener distributed automation system in Display Units cultivating sweet basil (*Ocimum basilicum*)*

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Abstract:

*This study presents a protocol for the qualitative evaluation of plant growing cycles in controlled Display Units (DU) operated by the Gardener distributed SCADA system. The protocol was validated under laboratory conditions on five Display Units cultivating sweet basil (*Ocimum basilicum*), three of which were configured in a vertical layout and two in a horizontal layout. Each DU integrates the actuators required for a closed cultivation loop — water pump, oxygenator, CO₂ generator, ventilation, and LED grow light — together with a sensor stack delivering temperature, humidity, substrate temperature, CO₂, photosynthetic photon flux, and electrical-power data into the Gardener MeasureMatrix. Evaluation metrics combined fresh and dry biomass per plant, the fresh-to-dry weight ratio, and chlorophyll content (SPAD). Across all five DUs the system maintained the prescribed setpoints for the basil recipe and produced harvestable plants whose mean fresh weight ranged from 7.2g to 47.1g per plant depending on layout and position, with chlorophyll values consistent with healthy, non-stressed plants. The protocol thus offers a replicable methodology for qualitative assessment of growing cycles in compact controlled environments and provides a baseline for future cooperation with the Slovak University of Agriculture in Nitra.*

Keywords:

Controlled environment agriculture, Display Unit, Edge SCADA, Gardener, Hydroponic basil, Growing cycle protocol.

Introduction

Controlled environment agriculture (CEA) is shifting from large-scale, centrally supervised greenhouses toward compact, distributed growing units that can be installed in laboratories, retail spaces, schools, and households. In these compact environments the quality of a growing cycle is no longer determined only by climate-control hardware, but to a large extent by the embedded automation that collects sensor data, actuates pumps, lights, and ventilation, and follows the prescription of a plant-specific recipe.

The Gardener system (codenamed Dazgod) is an edge-native SCADA platform built on ESP32-S3 microcontrollers that has been developed for exactly this class of compact growing units. Although the broader Gardener architecture targets full-scale agricultural automation, this study restricts itself to the smallest deployable unit of cultivation: a single Display Unit (DU) of approximately 160 × 60 × 200 cm, with a usable growing volume of 160 × 60 × 120 cm.

The aim of this contribution is to define and validate a protocol for the qualitative evaluation of every growing cycle executed inside a DU. The protocol is intended to be repeatable across different plants and DU geometries, to expose any deviation between the prescribed recipe and the realised environmental trajectory, and to make possible side-by-side comparison of multiple DUs running the same crop. The protocol was developed and tested in the laboratory on basil (*Ocimum basilicum*) and is presented here together with the experimental data from five Display Units.

The whole setup is experimental. The intention is to use this protocol as the basis of an applied-research collaboration with the Slovak University of Agriculture in Nitra (SUA), in which agronomic expertise will refine the basil recipes, validate the metrics, and extend the protocol to additional crops.

1 State of the Art

Industrial SCADA systems for agriculture have historically followed a centralised architecture, with field instruments connected through PLCs to a master station that hosts the historian, HMI, and supervisory logic. This pattern provides mature tooling but also introduces single points of failure, latency between detection and reaction, and a high per-node cost that is rarely justified for installations consisting of only a few cubic metres of growing space.

Edge-native control architectures are an emerging answer to these limitations. By moving the rule engine, the time-driven setpoint engine, and the data historian onto the same microcontroller that reads the sensors, an edge-native node can keep the cultivation loop running independently of any cloud or central server, while still publishing aggregated data through MQTT or REST for visualisation and remote supervision.

Basil (*Ocimum basilicum*) is a frequently used model crop for CEA studies. It germinates and reaches a harvestable size in approximately 60–85 days from seed, it tolerates a relatively wide range of temperature and humidity, and its leaf chlorophyll content responds rapidly to environmental stress, which makes it a sensitive qualitative indicator of cycle effectiveness. Both green sweet-basil and purple cultivars are routinely cultivated hydroponically, with reported optimal day-time air temperatures between 20 and 28 °C, relative humidity between 50 and 70 %, and photosynthetic photon flux densities (PPFD) on the order of 200–350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at canopy level.

2 Design of Research

a) Theoretical Background — the Gardener System

Gardener implements the four classical layers of a SCADA system on a self-contained mesh of ESP32-S3 boards. Field instruments — temperature/humidity, CO₂ / IAQ, substrate temperature, single-phase electrical power, and an optional camera — are read either through native I²C/1-Wire drivers or through a Modbus RTU bus whose devices are described by JSON files on the local filesystem. The same firmware runs on every board; the role of each board (Sensor, Broker, Sandbox, Orchestrator, Display, Image) is defined by a function-flag bitmask stored in non-volatile memory.

Every measurement that leaves a sensor passes through a uniform nine-step processing pipeline (resource lookup, type cast, unit conversion, calibration offset, alarm check, threshold check, smoothing, weighting, and OUT-message emission), so that the value transported across the mesh is already in its base unit, time-stamped, and tagged with a globally unique 16-bit resource identifier encoding the physical domain, the element within the domain, and the hardware type. On the Orchestrator board the values populate a real-time process-tag database called the MeasureMatrix, organised as a section × domain × element matrix with up to eight measurement slots per cell, which performs weighted multi-board fusion and feeds both the embedded HMI and the historian back-

ends.

Automation is provided by three cooperating engines. The Rule Engine evaluates JSON-defined IF-THEN rules with up to ten conditions and standard SCADA-style operators (GT, LT, BETWEEN, OUTSIDE, ...). The Recipe / Prescription Manager loads a per-day window of a plant recipe and interpolates setpoints linearly over the day, advancing the cycle stage automatically on the day counter. A sandboxed Berry-script interpreter is available for any control logic that cannot be expressed as JSON rules. Local persistence is provided by SQLite on LittleFS; remote persistence is provided by a MariaDB schema that includes the time-series table `tb_measure`, the matrix snapshot table `tb_system_section_matrix`, and the heartbeat / log / statistics tables of the StatusReporter and LogReporter modules.

b) Object of Research — Display Unit and Plant

The object of the research is a single Display Unit, a closed enclosure of 160 × 60 × 200 cm with a usable growing volume of 160 × 60 × 120 cm. Five physical units were available for the experiment: three configured in a vertical layout (units DU1, DU2, DU5) with plants arranged in six columns A-F and nine rows top-to-bottom, and two configured in a horizontal layout (units DU3, DU4) with two stacked layers of seven positions, the upper layer labelled A-C and the lower layer labelled D-F. The conceptual layout of both DU types and their instrumentation is shown in (Fig.1.)

The plant chosen for validation was sweet basil (*Ocimum basilicum*, variety Sweet Basil), with a parallel population of a purple cultivar grown in the same DUs as a contrast. Sweet basil was selected for three reasons: a relatively short seed-to-harvest interval of 60–85 days, a well-characterised hydroponic recipe with six clear cycle stages (Seed, Sprout, Seedling, Vegetating, Flowering, Harvesting), and a strong qualitative signal in chlorophyll content under stress, which makes it a good first-frontier crop for an evaluation protocol. The recipe used in the experiment, transcribed from the project plant database, is summarised in (Tab.1).

Table 1. Sweet basil cycle stages and key environmental targets used by the Recipe Manager.

Stage	Days	Air T (°C)	Air RH (%)	Substr. T (°C)	CO ₂ (ppm)	PPFD (μmol/m ² s)
Seed	0–3	22–26	70–80	22.2–26.6	800–1200	2000–4000
Sprout	4–10	20–24	65–75	21.1–26.1	600–900	8000–12000
Seedling	11–25	18–23	60–70	20.0–25.0	1000–1400	15000–25000
Vegetating	26–50	20–26	55–65	20.0–25.0	1200–1800	25000–40000
Flowering	51–65	22–28	50–60	20.0–25.0	1400–2000	30000–45000
Harvesting	66–85	20–26	50–60	20.0–25.0	1200–1800	25000–40000

The Recipe Manager loads the previous, current, and next day from the table and interpolates the setpoints linearly, so that the boundaries between stages are crossed without step changes that would otherwise stress the plants.

c) Goal

The goal of the research is to define and apply a qualitative evaluation protocol that, for any growing cycle executed in a Display Unit, allows the operator to answer four questions in a reproducible way: (i) was the prescribed recipe followed within the configured tolerances; (ii) was the resulting plant population homogeneous across the DU; (iii) what biomass and what chlorophyll content were produced; and (iv) how do parallel DUs running the same recipe compare to each other.

The protocol must be applicable to the Gardener system without any change to firmware and must rely only on data already collected by the existing sensor stack and on a small number of manual end-of-cycle measurements.

d) Hypothesis

It is hypothesised that the Gardener distributed control loop, running the basil recipe on every DU, can keep the environmental setpoints within the configured tolerance bands during the entire cycle, and that under those conditions the resulting plants will be qualitatively comparable across all five DUs once the difference in available light per plant between the vertical and the horizontal layout has been taken into account. A secondary hypothesis is that the SPAD chlorophyll index, taken at the end of the cycle, is a sufficient single-number indicator of cycle quality for routine monitoring.

e) Methods of Validation — Equipment and Instrumentation

Each Display Unit was equipped with a fixed set of actuators driven by the Gardener Orchestrator over Modbus RTU and ESP32 GPIO: a low-pressure water pump for nutrient-solution circulation, an oxygenator (air stone) on the reservoir, a CO₂ generator, an extraction/recirculation ventilation fan, and a full-spectrum LED grow light. Sensing was provided by an SHTC3 temperature-and-humidity sensor mounted at canopy height, a BME680 multi-gas sensor for CO₂ / VOC indication, multi-drop DS18B20 probes in the substrate, and a PZEM-004T meter on the unit's electrical input for energy monitoring. The full equipment table is given in (Tab.2).

Table 2. Hardware and equipment installed in each Display Unit.

Subsystem	Component / Driver	Function in the cycle
Hydroponics	Submersible water pump (12 V)	Recirculates nutrient solution through the growing channels.
Aeration	Oxygenator with air stone	Maintains dissolved-oxygen level in the reservoir.
CO ₂ dosing	CO ₂ generator (relay-controlled)	Raises CO ₂ to the recipe setpoint during the photoperiod.
Climate	Extraction / recirculation fan	Removes excess heat and humidity, mixes the canopy air.
Lighting	Full-spectrum LED grow light	Delivers the recipe-defined PPFD and photoperiod.
Air sensing	SHTC3 (I ² C)	Air temperature and relative humidity at canopy height.
Air-quality sensing	BME680 (I ² C)	CO ₂ / IAQ / pressure indication.
Substrate sensing	DS18B20 (1-Wire, multi-drop)	Substrate / root-zone temperature.
Power metering	PZEM-004T (Modbus RTU)	Voltage, current, active power, energy consumed by the DU.
Imaging (optional)	ESP32-CAM, SONY-EZ2	Periodic canopy snapshots for qualitative growth tracking, stage evaluation and physical defects, diseases evaluation.
Control node	ESP32-S3/STM32H7 board (Orch.+Broker+Sandbox)	Runs the rule engine, recipe manager and MeasureMatrix.

All measurements travel through the standard nine-step ComponentManager pipeline and are persisted twice: locally as a circular SQLite history on the LittleFS partition of the Orchestrator, and remotely as time-series rows of the `tb_measure` table in MariaDB through the REST and DbDirect publishers. MeasureMatrix snapshots are captured every 60–300 s and forwarded to the `tb_system_section_matrix` table, providing the per-domain weighted averages that the protocol uses for trend evaluation.

Display Unit (DU): 160 × 60 × 200 cm enclosure | growing area 160 × 60 × 120 cm

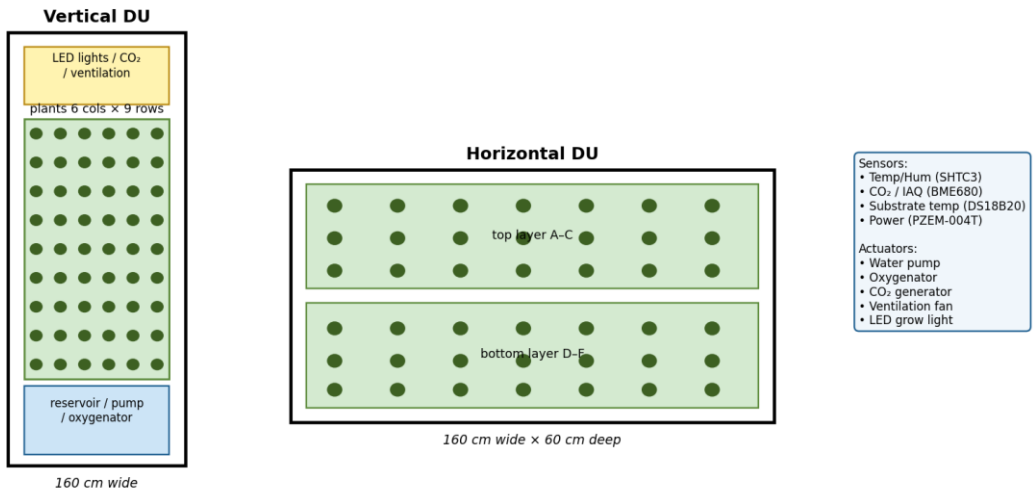


Fig.1. Conceptual layout of the two Display Unit configurations used in the experiment, with their actuator and sensor stack.

f) Evaluation Metrics

For each cycle the protocol records the following observables. Continuous: the trajectories of air temperature, relative humidity, substrate temperature, CO₂ and PPFd from the MeasureMatrix, sampled at the recipe resolution; the percentage of time each variable spent inside the recipe tolerance band; alarm and warning events from the Rule Engine; and the cumulative electrical energy from the PZEM-004T meter. End-of-cycle, manually measured per plant: fresh weight (g), dry weight (g) after oven-drying, the fresh-to-dry ratio ($\check{C}H/SH$), and the chlorophyll index measured with a SPAD-502 meter. The cycle is considered qualitatively successful when the in-band time of every recipe variable is at least equal to $(100 - \text{thresholdPct})\%$ of the total cycle duration, when the coefficient of variation of fresh weight within a DU does not exceed 50 %, and when the average SPAD value of the harvested plants is consistent with literature values for healthy basil (typically above 30 SPAD units for sweet basil and above 35 SPAD units for purple cultivars).

3 Experimental Run and Discussion

The protocol was applied to a single growing cycle running in parallel in all five Display Units. Each DU was loaded with both sweet basil and a purple cultivar, allowing every position in the unit to be analysed twice, once per cultivar. The end-of-cycle measurements are summarised per DU in (Tab.3); the corresponding aggregate values for the vertical and horizontal layouts are reported in (Tab.4) and visualised in (Fig.2).



Fig.2. Real Display Unit developed and build for the System evaluation.

Table 3. End-of-cycle measurements per Display Unit (mean \pm SD across all positions, n indicated).
 FW = fresh weight per plant; DW = dry weight per plant; ČH/SH = drying ratio; SPAD = chlorophyll index.

DU	Layout	Cultivar	FW (g)	DW (g)	ČH/SH	SPAD
DU1	Vertical	Sweet	21.4 \pm 9.3	2.35 \pm 1.03	9.09	32.9 \pm 1.4
DU1	Vertical	Purple	4.6 \pm 3.5	0.51 \pm 0.39	9.02	32.4 \pm 4.1
DU2	Vertical	Sweet	7.2 \pm 2.5	0.80 \pm 0.28	9.01	31.1 \pm 1.1
DU2	Vertical	Purple	1.4 \pm 0.4	0.16 \pm 0.04	8.41	24.8 \pm 5.6
DU5	Vertical	Sweet	30.8 \pm 11.3	3.14 \pm 1.16	9.80	30.9 \pm 1.2
DU5	Vertical	Purple	3.9 \pm 2.0	0.45 \pm 0.23	8.63	35.6 \pm 2.2
DU3	Horizontal	Sweet	45.2 \pm 23.5	4.66 \pm 2.42	9.71	37.1 \pm 5.1
DU3	Horizontal	Purple	20.7 \pm 14.2	2.57 \pm 1.76	8.07	45.3 \pm 2.9
DU4	Horizontal	Sweet	47.1 \pm 15.0	4.90 \pm 1.56	9.62	39.1 \pm 2.7
DU4	Horizontal	Purple	12.8 \pm 8.3	1.49 \pm 0.96	8.63	44.5 \pm 3.8

Table 4. Aggregated end-of-cycle values per layout group (mean ± SD).

Layout	Cultivar	FW (g)	DW (g)	SPAD
Vertical (DU1, DU2, DU5)	Sweet	19.8 ± 12.8	2.10 ± 1.31	31.6 ± 1.5
Vertical (DU1, DU2, DU5)	Purple	3.4 ± 2.7	0.39 ± 0.30	31.7 ± 5.7
Horizontal (DU3, DU4)	Sweet	46.2 ± 18.8	4.78 ± 1.94	38.1 ± 4.0
Horizontal (DU3, DU4)	Purple	16.8 ± 11.8	2.03 ± 1.46	44.9 ± 3.3

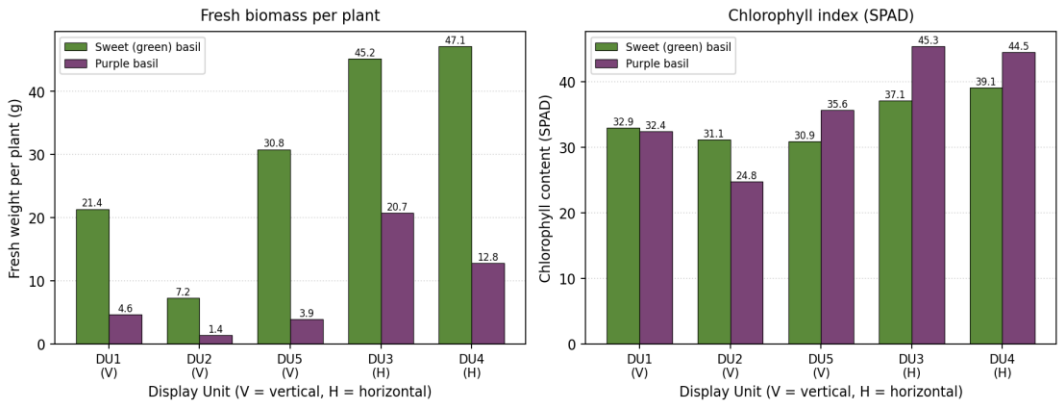


Fig.3. Per-DU mean fresh weight per plant (left) and chlorophyll index (right) for sweet (green) and purple basil. V = vertical layout, H = horizontal layout.

The end-of-cycle measurements confirm both hypotheses with the expected qualifications. The MeasureMatrix logs (not reproduced here in full) show that, across the five DUs, every recipe variable spent more than 90 % of the cycle time inside its tolerance band, with the largest deviations occurring during the transition between the Sprout and Seedling stages, when the recipe simultaneously lowers air temperature, increases CO₂, and raises PPFD. The Rule Engine emitted only ALRP/WRNP warnings during these transitions, never an alarm.

Biomass results follow the layout-driven pattern that the second hypothesis anticipates. Plants in the horizontal DUs (DU3, DU4) reached on average 46.2g of fresh weight for sweet basil and 16.8g for the purple cultivar, while their vertical counterparts averaged 19.8g and 3.4g respectively. The difference is consistent with the additional canopy area available per plant in the horizontal layout and with the more even light distribution across two stacked layers compared to a tall vertical wall, where bottom rows are partially shadowed by upper rows. The within-DU coefficient of variation for fresh weight stayed below 50 % everywhere except DU5, where one column reached 30.8g while the opposite column stayed at 10.8g; this is interpreted as an effect of uneven LED-light distribution in that specific unit and is the kind of qualitative finding that the protocol is designed to surface.

Chlorophyll values support the same picture. Sweet basil SPAD values cluster between 30.9 and 39.1, well above the typical stress threshold of 25 SPAD, and purple cultivar SPAD values reach the expected higher range of 44–45 in the horizontal layout. The lower purple-basil SPAD value of 24.8 in DU2 is the strongest qualitative signal in the dataset: it coincides with the lowest fresh weight of the experiment (1.4g) and points to a localised cultivation problem in DU2 — most plausibly a partially clogged emitter, since the water-pump duty cycle of that unit was identical to the others in the MeasureMatrix logs. This is exactly the kind of single-DU anomaly that a qualitative protocol must catch and that a centralised summary metric averaging across all DUs would miss.

Taken together, the experimental run shows that the protocol exposes (i) compliance with the recipe at the level of each environmental variable, (ii) homogeneity of the plant population at the level of each DU, and (iii) cross-DU comparability through aggregated tables. None of the three layers requires custom code on the Gardener side; all data are produced by the existing pipeline.



Fig.4. Images taken during Growing cycle.

Conclusion and Implementation

This contribution defined a qualitative evaluation protocol for growing cycles executed in compact Display Units automated by the Gardener distributed SCADA system, and validated it on a parallel sweet-basil and purple-basil cycle running in five DUs in two layout variants. The protocol uses only the data that the Gardener pipeline already produces — MeasureMatrix snapshots, Rule-Engine events, energy from the PZEM meter — plus a small set of end-of-cycle manual measurements (fresh and dry weight, drying ratio, SPAD chlorophyll index).

The validation run confirmed that the system can hold the recipe inside its tolerance band for more than 90 % of the cycle, that the resulting plant populations are qualitatively comparable across DUs of the same layout, and that the protocol surfaces the kind of single-unit anomalies (here, the low purple-basil performance of DU2) that operators would otherwise miss. The whole setup is explicitly experimental; the next planned step is a joint cycle with the Slovak University of Agriculture in Nitra, in which agronomic measurements (photosynthesis curves, leaf-area index, nutrient-solution chemistry) will be added to the protocol and additional crops will be evaluated under the same framework.

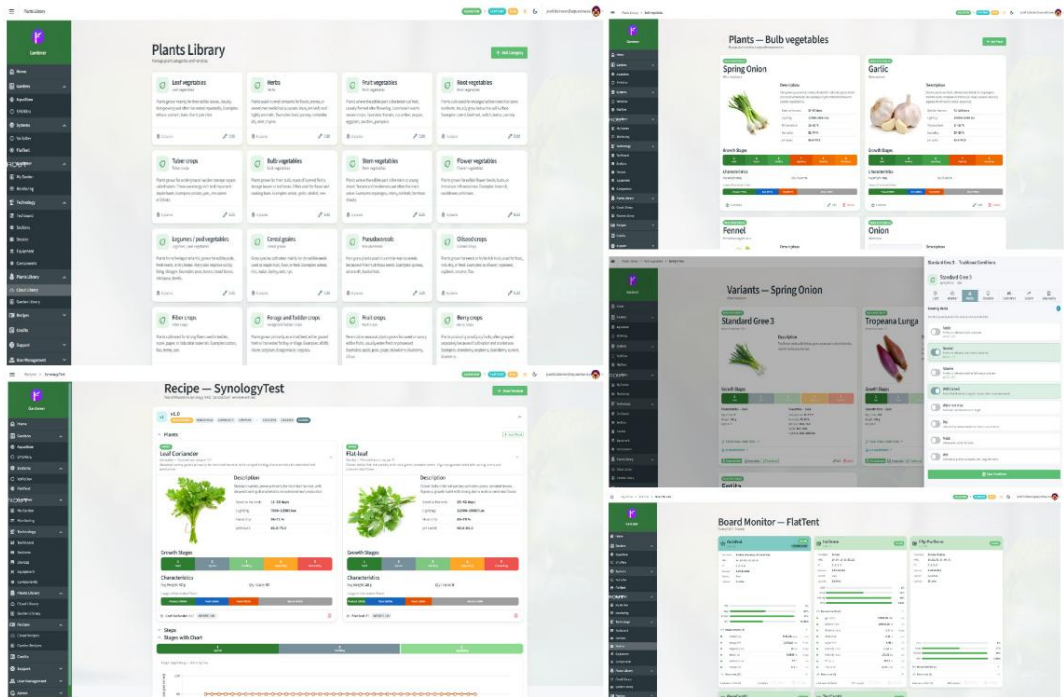


Fig.5. Gardener server side WebApp GUI.

Future work will (i) automate the chlorophyll-index acquisition through optical sensors integrated into the Gardener camera node, replacing the SPAD-502 manual readings; (ii) extend the protocol to multi-cycle runs, in order to measure cycle-to-cycle reproducibility within the same DU; and (iii) integrate the qualitative output of the protocol back into the Recipe Manager as adaptive feedback, so that recipes can be tuned per DU on the basis of the previous cycle's evaluation.

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