A way to increase crop science productivity

A P Grishin*, A A Grishin, V A Grishin and N A Semenova
Federal Scientific Agroengineering Center VIM, Moscow, Russian Federation

*E-mail: 5145411@mail.ru

Abstract. It is shown that in earlier studies, the results of which were reported in the article "Digital wireless mini-sensor of plant thermoregulation", the presence of three phases of the thermoregulation process was experimentally revealed, and the task of further research aimed at theoretical and experimental confirmation of the hypothesis was set that the maximum productivity of the plant is ensured at the optimum air temperature and the maximum consumption of the nutrient solution. A number of statements, which do not require proof, are presented about the relationship between photosynthesis and air temperature and their effect on productivity. The article sets the task of developing a universal algorithm for maintaining the air temperature. Thermoregulation processes of plants were chosen as the object of research. These included the temperature of the leaf surface, the temperature difference between the leaf surface and the ambient air, and the flow rate of water for cooling evaporation. Two plant samples were chosen as the subject of research: salad variety "Red Dubolistsny" and tomato variety "Fighter" (Buyan). The change in the mass of water in the container was measured using an ML-A01 balance with a measurement accuracy of 0.01 g, and the temperature was measured with an infrared IR thermometer Kelvin IKS 4-20 / 5. Data were recorded at 5-minute intervals and repeated three times over a short period of time. The plants were placed in containers with an airtight lid, which contains an oil seal for the plant stem. Moreover, the roots were placed under a lid with an aqueous nutrient solution. At the boundary of phase 2, there is a zone of maximum consumption of nutrient solution through plants, while the temperature is optimal, which corresponds to the maximum rate of photosynthesis. Further, the object of research was the process of forming a productive mass in a plant, depending on the air temperature. The weight of the plant was measured separately, on more accurate scales of the ML-A01 brand with a measurement limit of 100 g and a graduation of 0.01 g, twice a day: in the morning and in the evening. Next, weight gain dependence graph on the air temperature was built and the trend was found in the form of a second-order polynomial, which had a maximum. Its coordinates are 29.29 °C and 0.75 g of green weight gain. The maximum increase is provided at an air temperature corresponding to the boundary of phases 2 and 3. From previous studies, we found this value, it was 29.36 °C, that is it differs by 0.2%.

1. Introduction
The final stage in the development of the leaf thermoregulation sensor was laboratory tests in the course of an experiment on the study of thermoregulation processes in tomato sample of “Fighter” variety. The results of which were reported in the article "Digital wireless mini-sensor of plant thermoregulation", where the presence of three phases of the thermoregulation process of plants was experimentally revealed and the task of further research aimed at theoretical and experimental confirmation of the
hypothesis that the maximum plant productivity is provided at optimal temperature was set air and maximum consumption of nutrient solution.

Digital agriculture, and in particular agricultural production based on closed artificial agroecosystems (CAAES), is distinguished by the possibility and necessity of regulating agroecological parameters. This need entails the ability to ensure maximum plant productivity. One of these adjustable parameters is the ambient temperature. However, the question “what is the best temperature for a particular plant” remains open, since each plant has a different temperature value [1,2].

Thus, the task is to develop a universal algorithm for maintaining the air temperature in the (CAAES), which ensures the maximum productivity of the plant, regardless of its type and stage of growth.

We will accept the following statements as not requiring proof [3-7]:

- in accordance with the law of survival, the plant tries to ensure maximum productivity by creating certain conditions for this;
- the rate of photosynthesis directly affects the productivity of the plant;
- the rate of photosynthesis depends on the ambient temperature;
- there is a certain optimal value of the ambient temperature at which the maximum rate of photosynthesis is ensured;
- each plant, at least each plant species, has its own individual optimum temperature at which the rate of photosynthesis is maximum;
- the plant is able to regulate its temperature to ensure its optimum in only one way - through evaporative cooling;
- the plant uses its maximum cooling capacity to provide an optimal temperature that guarantees the maximum rate of photosynthesis;
- evaporative cooling has a cooling effect limit.

From the above studies, it follows that each plant has three phases of the thermoregulation process due to the ambient temperature when it changes from a certain minimum to a certain maximum. However, we are interested in the second phase, where the optimal temperature is provided for the maximum rate of photosynthesis and the plant has the only tool for this - evaporative cooling. Let us recall the characteristics of the second phase [8, 9].

Phase 2. The ambient temperature is higher than optimal, but the stomatal apparatus is working and the plant is able to cool itself. The plant lowers its own temperature by evaporating moisture from the leaf surface. The cooling capacity is sufficient to cool the plant temperature to optimum. In this case, there is a difference between the ambient temperature and the temperature of the plant [10,11,12].

Let us accept the following working hypotheses [13-15]:

- The highest rate of photosynthesis exists with the highest consumption of evaporative cooling. At optimum leaf temperature, the greater the moisture consumption caused by evaporative cooling, the more nutrient solution will pass through the plant.
- Moisture consumption during evaporative cooling is directly dependent on the difference in ambient temperatures and leaf temperatures. The maximum moisture consumption occurs at the maximum temperature difference.
- After reaching maximum cooling capacity, the plant reaches maximum evaporative cooling, which stops growing. That is, a plateau of maximum thermoregulation flow rate is noted. The difference between the ambient temperature and the leaf temperature reaches its maximum.
- The highest productivity ($R_{max}$) is provided at the optimum temperature and maximum flow rate: at the border of zone 2 and zone 3.

These 3 phases (stages) are shown graphically in figure 1.
If the hypothesis is confirmed that the maximum productivity is ensured at the optimum temperature and maximum flow rate, it is necessary to develop a temperature control algorithm that searches for the temperature at the boundary of stages 2 and 3. This algorithm corrects the ambient temperature and controls the difference between the leaf and ambient temperatures, determining the maximum their difference at the lowest possible value of the air temperature, that is:

\[
\begin{align*}
T_{\text{min air}} & \land \\
\Delta T_{\text{max}} & \Rightarrow R_{\text{max}}
\end{align*}
\]

Thus, the purpose of the research at the first stage is to experimentally show the presence of the indicated phases of the leaf temperature when the ambient temperature changes from a minimum value to a certain maximum, as well as the correspondence of the maximum evaporation rate to the maximum difference in leaf and air temperatures. At the second stage of research, it is experimentally to show that the highest productivity corresponds to the temperature regime at the boundary of phases 2 and 3.

2. Material and methods

Thermoregulation processes of plants were chosen as research object. These included the temperature of leaf surface, the temperature difference between the surface of leaf and the ambient air, and the flow rate of water for cooling evaporation.

Two plant samples were chosen as research subject: salad variety "Red Dubolistny" and tomato variety "Fighter" (Buyan).

The plants were placed in containers with an airtight lid, which contains an oil seal for the plant stem. Moreover, the roots were placed under the lid with an aqueous nutrient solution, and the plant itself was above it, figure 2.

The change in the mass of water in the container was measured using an ML-A01 balance with a measurement accuracy of 0.01 g, and the temperature was measured with an infrared IR thermometer Kelvin IKS 4-20 / 5, figure 2. Data were recorded in a digital format [16] with a five-minute interval and threefold repetition, over a short period of time, however, in order to exclude the influence of plant
growth on the weight data, the mass of evaporated water was determined by calculation through the value of the difference in air and leaf temperatures according to a known formula given in [17].

![Figure 2. Tomato in a container with IR sensor leaf surface temperature.](image)

3. Results and its discussion
We will consider the results for each plant species.

3.1. Tomato variety "Fighter" (Buyan)
The measured average temperatures and the mass of evaporated water are summarized in table 1.

**Table 1.** Average values of temperatures and mass of evaporated water for tomato.

| No. values | Leaf temperature, °C | Air temperature °C | The difference between leaf and air temperatures, °C | Evaporated water mass, g |
|------------|-----------------------|--------------------|-----------------------------------------------------|--------------------------|
| 1          | 29.65                 | 29.75              | 0.1                                                 | 1.15                     |
| 2          | 29.9                  | 30                 | 0.1                                                 | 1.15                     |
| 3          | 30                    | 30.31              | 0.31                                                | 3.56                     |
|   |   |   |   |   |
|---|---|---|---|---|
| 4 | 29.92 | 30.44 | 0.52 | 5.97 |
| 5 | 29.83 | 30.56 | 0.73 | 13.78 |
| 6 | 29.53 | 30.75 | 1.22 | 15.97 |
| 7 | 29.53 | 30.75 | 1.22 | 15.97 |
| 8 | 29.25 | 30.69 | 1.44 | 15.28 |
| 9 | 29.23 | 30.69 | 1.46 | 15.28 |
| 10 | 29.35 | 30.81 | 1.46 | 16.65 |
| 11 | 29.21 | 30.88 | 1.67 | 17.46 |
| 12 | 29.35 | 31.05 | 1.7 | 19.41 |
| 13 | 29.27 | 31.1 | 1.83 | 19.99 |
| 14 | 29.35 | 31.23 | 1.88 | 21.48 |
| 15 | 29.25 | 31.15 | 1.9 | 20.56 |
| 16 | 29.25 | 31.31 | 2.06 | 22.40 |
| 17 | 29.34 | 31.5 | 2.16 | 24.58 |
| 18 | 29.42 | 31.81 | 2.39 | 28.14 |
| 19 | 29.31 | 32.19 | 2.88 | 32.50 |
| 20 | 29.61 | 32.44 | 3.08 | 35.38 |
| 21 | 29.73 | 32.63 | 3.09 | 35.49 |
| 22 | 30.23 | 33.00 | 3.10 | 35.61 |

Based on the given data, let us build a graph, figure 3.

Experimental studies of thermoregulation of two samples of tomato and salad plants have confirmed that there are three phases of plant thermoregulation: the graphs show that in phase 1 the ambient temperature is below optimal and the leaf temperature and ambient temperature are close or equal. Phase 2 - the ambient temperature is higher than the optimal one and the plant reduces its own temperature due to the evaporation of moisture from the leaf surface to a certain constant value. This value is maintained for some time due to evaporative cooling while the stomatal work is possible for this. Phase 3 - the ambient temperature is so much higher than the optimum that the plant has reached its cooling capacity and the plant temperature begins to rise following the ambient temperature. In this case, the temperature difference is constant. At the boundary of phase 2, there is a zone of maximum consumption of nutrient solution through plants, while the temperature is optimal, which corresponds to the maximum rate of photosynthesis.

On the graphs, the leaf temperature in phase 2 has random deviations from a constant value, which is caused by objective reasons for plant growth and this randomness must be confirmed. To do this, we will carry out statistical processing of the measurement results by the "Sequential differences" method [18], which makes it possible to check the time series of the leaf temperature for the random nature of deviations of its values from the expected value, for which the actual $\tau_f$ and theoretical $\tau_t$ criteria are determined. If $\tau_f > \tau_t$, then the deviations are random and the temperature can be considered constant and equal to the mathematical expectation. The test results are summarized in table 3.
3.2. «Red Dubolistny» salad
The measured average temperatures and the mass of evaporated water are summarized in table 2.

Table 2. Average values of temperatures and mass of evaporated water for salad.

| No. values | Leaf temperature, °C | Air temperature, °C | The difference between leaf and air temperatures, °C | Evaporated water mass, g |
|------------|-----------------------|----------------------|--------------------------------------------------|--------------------------|
| 1          | 20.88                 | 20.09                | 0.79                                             | 0.37                     |
| 2          | 23.31                 | 22.23                | 1.08                                             | 0.50                     |
| 3          | 24.81                 | 24.03                | 0.78                                             | 0.36                     |
| 4          | 25.38                 | 22.93                | 1.98                                             | 0.92                     |
| 5          | 25.81                 | 22.67                | 3.14                                             | 1.46                     |
| 6          | 26.25                 | 22.83                | 3.42                                             | 1.59                     |
| 7          | 26.94                 | 23.39                | 3.55                                             | 1.65                     |
| 8          | 27.56                 | 24.17                | 3.39                                             | 1.58                     |
| 9          | 28.19                 | 24.43                | 3.76                                             | 1.75                     |
| 10         | 28.69                 | 25.05                | 3.64                                             | 1.69                     |
| 11         | 29.25                 | 25.81                | 3.44                                             | 1.60                     |
Based on the given data, let us build a graph, figure 4.

**Figure 4.** Thermoregulation phases of salad plant.
Table 3. Results of calculating statistical characteristics.

| Parameters                                      | Salad  | Tomato |
|------------------------------------------------|--------|--------|
| Value number of phase 2                        | 5…9    | 5…17   |
| Mathematical expectation (ME)                  | 23.40  | 29.36  |
| Mean-square deviation (MSD)                    | 0.74   | 0.03   |
| Variance                                       | 0.55   | 0.17   |
| The lower border of con. interval              | 20.45  | 30.06  |
| The upper border of con. interval              | 23.40  | 28.67  |
| Actual and theoretical criteria calculation for successive differences method |        |        |
| $\Sigma a^2$                                   | 1.47   | 0.25   |
| $C^2$                                          | 0.59   | 0.01   |
| $\tau_f$                                       | 1.07   | 0.35   |
| $\tau_t$                                       | 0.02   | 0.15   |

So, it has been established that the process of thermoregulation can be represented by three phases, and the area at the border of phases 2 and 3 is characterized by the highest rate of photosynthesis, since the temperature in it has an optimal steady-state value, and the greatest supply of nutrients to the plant, since the mass of evaporated water in it reaches the maximum magnitudes.

That is, this area for the corresponding value of the air temperature is the most productive. In other words, this temperature, or rather its range, in which the stomata retain their working capacity and are able to cool the plant, enables the photosynthetic apparatus to work with the greatest efficiency, and the plant itself receives more nutrients [19]. That is, conditions are created to increase productivity. Thus, further the object of research will be the process of formation of the productive mass of the plant, depending on the air temperature. Let us numerically verify that productivity in the area under consideration will be the most important. The check will be carried out on a tomato sample, for which we will use the results of the studies carried out on the necessary characteristics of the growth of green weight when it is exposed to various air temperatures. Measurements of processes characteristics were carried out on the recorder automatically with a threefold repetition from 3.04. until 04/19/2020. The measured data were archived in a CD and then processed on a computer in the "Exel" environment. The measurements of the growth of the productive weight were carried out by weighing the plant with the lid after subtracting the weight of the lid measured in advance. The weight of the plant was measured separately, on more accurate scales of the ML-A01 brand with a measurement limit of 100 g and a graduation of 0.01 g, twice a day: in the morning and in the evening. The measurements were carried out at different air temperatures, after which the average value of the measured series of productivity growth was calculated for each repetition of air temperature values. Next, we conduct research for a given air temperature.

Five values were selected from the entire calculated series of air temperatures. Having an increase from 26 to 34 ℃, table 4.

Table 4. Changes in productivity depending on air temperature.

| Average air temperature | 26.55 | 27   | 28.76 | 30.29 | 33.65 |
|-------------------------|-------|------|-------|-------|-------|
| Plant weight change, gr | 0.62  | 0.5  | 0.72  | 0.79  | 0.23  |

Then we built a graph and found a trend in the form of a second-order polynomial, which has a maximum, figure 5. Its coordinates are 29.29 ℃ and 0.75 g of green mass gain. The maximum increase is provided at air temperature corresponding to the boundary of phases 2 and 3. From previous studies, we found this value, it was 29.36 ℃, that is it differs by 0.2%.
Figure 5. Dependence of tomato plant growth on air temperature.

4. Conclusions
Studies have confirmed the presence of three phases in the thermoregulation of the plant growth process, and the area at the border of the 2 and 3 phases is characterized by the highest rate of photosynthesis, since the temperature in it has an optimal steady-state value, and the greatest supply of nutrients to the plant, since the mass of evaporated water in it reaches maximum value.

Phase 2 is of the greatest interest, since the temperature in it is stabilized by the evaporative cooling process and for tomato it is equal to 29.36 °C, and for lettuce 23.4 °C. This temperature is optimal in terms of the maximum rate of photosynthesis.

Studies have confirmed the hypothesis of maximum increase presence in productivity at a certain air temperature. This temperature, or rather its range, in which the stomata still retain their working capacity and are able to cool the plant, enables the photosynthetic apparatus to work with the greatest efficiency, and the plant itself receives more nutrients.

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