Photosynthetic activity of soybean crops in response to different sowing times under the environmental conditions of the Russian Far East

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Abstract. The aim of this study was to determine the optimal sowing time for photosynthetic activity in the soybean varieties «Batya» and «Khabarovskiy Yubilyar» in the Russian Far East. We studied the influence of several parameters that induce photosynthetic activity on the productive qualities of soybean seeds from these varieties at different sowing dates. Studies have shown that the factor which most significantly determines biological productivity is leaf area. Here, leaf area accounted for 92.3% of the total productivity, with 77.3% depending on the photosynthetic potential of the soybean plants. Optimal conditions for the growth of soybean leaves and the duration of their function were created during the May sowing dates. The leaf area of «Batya» and «Khabarovskiy Yubilyar» varieties decreased by 6–36% and 11–27%, respectively, at later sowing dates. The lowest net photosynthetic productivity in «Batya» was 2.0 g/m\(^2\)/day during the late sowing period, and the maximum value recorded was 4.2 g/m\(^2\)/day when sowing was at the end of May. The lowest photosynthetic productivity for the variety «Khabarovskiy Yubilyar» (3.4 g/m\(^2\)/day) was also recorded in plants from the late sowing period.

1. Introduction
Soybean is one of the major agricultural crops in the world, owing to its unique biochemical composition and versatility [1]. Most of its yield (90–95%) depends on the plants’ photosynthetic activity. Photosynthesis forms the basis of a complex sequential chain of metabolic processes, that induces growth, development, and productivity in the plant [2-3]. Soybean belongs to a group of plants in which a fraction of the assimilated carbon dioxide is released from the leaves during respiration - while simultaneously undergoing photosynthesis - under light conditions [4]. Consequently, the actual amount of assimilated CO\(_2\) in soybean plants is significantly less than the level of photosynthesis carried out. As photorespiration reduces the efficiency of photosynthesis, many researchers considered it an unnecessary and even wasteful process [5-7].

Maximum productivity in each soybean variety can only be achieved by exploiting the solar energy and optimal light conditions available to each plant. This can be accomplished using varietal agricultural techniques that would most likely correspond to the biological characteristics of soybeans. For example, the sowing period is a key agricultural technique that exploits day length to suit a certain stage of plant development [8-10].
The objective of this study was to investigate the influence of sowing time on the photosynthetic activity of the soybean varieties «Batya» and «Khabarovskiy Yubilyar» in the Russian Far East.

2. Materials and methods
Field experiments were carried out in the fields of the Far East Agricultural Research Institute in 2018–2020 to monitor the photosynthetic activity of soybean plants. The soybean varieties «Batya» and «Khabarovsk Yubilyar» were selected from the FGBNU DVNIISH. The experiment was replicated four times, using a 4-m² plot area and a seeding rate of 40 plants/m². The sowing dates were determined based on the temperature regime and soil readiness. In 2018, 1st term: May 20; 2nd term: May 30; 3rd term: June 10. In 2019, 1st term: May 9; 2nd term: May 15; 3rd term: May 27; 4th term: June 5; 5th term: June 10; 6th term: June 17. In 2020, 1st deadline: May 5; 2nd term: May 12; 3rd term: May 19; 4th term: May 26; 5th term: June 2; 6th term: June 9. The objective of this research was to produce soybean plants from the varieties «Batya» and «Khabarovsk Yubilyar» with a growing season of 120–135 days.

All counts and observations were carried out according to generally accepted methods. Leaf area was determined using the method of incisions; photosynthetic productivity was determined according to the method described by A.A. Nichiporovich [11]. During the study, the parameters of photosynthetic activity, as well as the characteristics of productivity, were studied in the soybean plants (table 1).

| Indicator Variable                      |   |
|----------------------------------------|---|
| Maximum leaf area, thousand m²/ha      | x1|
| Photosynthetic potential (FP), million days/ha | x2|
| Net productivity of photosynthesis (NPF), g/m²/day | x3|
| Yield, t/ha                            | y1|
| Beans per plant, pcs                   | y2|
| 1000 seed weight, g                    | y3|
| Growth period, days                    | y4|
| Total temperature of the surface air layer, °C | y5|
| Rainfall, mm                           | y6|
| SHC                                    | y7|

Significant differences were determined using the LSD0.5 criterion. A correlation analysis was performed using rank correlation (Kendall τ) to establish the relationship between the studied indicators. Regression equations were constructed and determination coefficients (R²) were calculated to assess the impact of meteorological factors on the soybean productivity indicators.

3. Results
The meteorological conditions during the research period differed in terms of temperature and precipitation, allowing their effects on the photosynthetic activity of soybean plants to be comprehensively studied. The amount of precipitation during the growing season in 2018 varied from 439.4 mm to 462 mm. The sum of temperatures ranged from 2,182.3 °C to 2,487.2 °C and SHC was −1.87. The amount of precipitation in 2019 during the growing season was ranged from 646 mm to 814.2 mm, with an average of 507 mm. The sum of temperatures ranged from 2,042.4 °C to 2,616.9 °C and SHC was −3.12. The amount of precipitation in 2020 during the growing season varied from 630 mm to 685.2 mm. The sum of temperatures ranged from 2,196.3 °C to 2,551.9 °C and SHC was −2.6.

The maximum leaf area was formed during the bean filling phase. «Batya» plants differed in leaf shape and assimilation surface area by an average of 10% from «Khabarovskiy Yubilyar» plants. The maximum
leaf area varied from year to year—depending on the sowing time—at 48.4–75.9 thousand m²/ha for «Batya» and 61.2–82.4 thousand m²/ha for «Khabarovskiy Yubilyar» (Table 2). A steady downward trend was observed in the maximum leaf area of plants sowed in late June.

### Table 2. Indicators of photosynthetic activity of the soybean varieties «Batya» and «Khabarovsk jubilee» from different sowing dates.

|          | 1       | 2       | 3       | 4       | 5       | 6     | Xcp ± ΔXcp | V.% |
|----------|---------|---------|---------|---------|---------|-------|------------|-----|
| **«Batya»** |         |         |         |         |         |       |            |     |
| x1       | 75.9    | 49.1    | 48.4    | 58±8.9  | 17.1    |       |            |     |
| 2018     | 49.6    | 50.1    | 51.0    | 49.3    | 48.4    | 50±1.51| 2.9       |     |
| 2019     | 52.1    | 57.3    | 65.2    | 71.1    | 75.2    | 50.3   | 62±10.9   | 16.9|
| 2020     | 3.7     | 1.2     | 1.0     | 2.0     | 1.5     | 1.4    | 2±0.7     | 27.7|
| x2       | 1.3     | 1.5     | 1.7     | 2.0     | 1.5     | 1.4    | 2±0.3     | 16.0|
| 2018     | 1.7     | 2.0     | 2.6     | 3.2     | 3.5     | 1.6    | 2±0.8     | 32.7|
| 2019     | 4.2     | 2.5     | 2.3     | 3.0     | 2.6     | 2.5    | 3±0.3     | 24.8|
| 2020     | 2.6     | 2.5     | 3.0     | 3.7     | 4.0     | 2.0    | 3±0.8     | 25.6|
| **«Khabarovskiy Jubilyar»** |         |         |         |         |         |       |            |     |
| x1       | 68.5    | 62.4    | 61.3    | 64±9.6  | 6.1     |       |            |     |
| 2018     | 67.8    | 73.4    | 66.1    | 65.0    | 63.9    | 63.1   | 67±3.9    | 5.6 |
| 2019     | 69.9    | 73.2    | 82.4    | 79.3    | 61.2    | 59.9   | 71±9.7    | 13.0|
| 2020     | 3.2     | 2.5     | 2.3     | 3±0.7   | 17.7    |       |            |     |
| x2       | 3.0     | 3.8     | 2.7     | 2.3     | 2.3     | 2.3    | 3±0.6     | 20.1|
| 2018     | 3.4     | 3.7     | 4.1     | 3.9     | 3.0     | 2.8    | 3±0.6     | 14.7|
| 2019     | 4.1     | 3.7     | 3.9     | 4±0.5   | 5.1     |       |            |     |
| 2020     | 3.8     | 4.4     | 3.7     | 4.3     | 4.1     | 3.6    | 4±0.3     | 8.3 |
| x3       | 3.9     | 4.8     | 4.9     | 4.3     | 4.3     | 3.4    | 4±0.6     | 13.1|

During the soybean growing season, more leaves were formed in plants from the late sowing periods compared to those from the first sowing periods. This was due to optimal temperature conditions conducive to the growth and development of soybean in late May and early June. Therefore, during the research period, the average soil temperature (measured at a depth of 6 cm) was 8 °C for the first sowing period, and −22°C for the last sowing period. The benefits of late sowing dates over the early ones persisted until the onset of flowering; in subsequent developmental stages, the differences in leaf area indices according to the experimental variants were almost equivalent. Leaf development in soybean was significantly influenced by hydrothermal conditions and the growing season. Early-maturing varieties typically have fewer leaves and a smaller leaf surface than mid- and late-maturing varieties [12]. For both varieties, the maximum leaf area was generated from plants sowed in late May to early June. In plants sowed at later dates, the leaf area decreased by 6–36% for the «Batya» variety, and by 11–27% for the «Khabarovskiy Yubilyar» variety.

To determine the level of development of photosynthetic organs, it is important to measure the leaf surface area, as well as the level of photosynthetic activity in already formed leaves [13-19]. The physiological parameter that combines these indicators is the photosynthetic potential (FP). The intensity of photosynthetic activity in the crops was assessed by the value of the net productivity of photosynthesis (NPF). The FSP index of the «Khabarovskiy Yubilyar» variety was higher than that of the «Batya» variety and ranged from 2.3–4.1 million days/ha and 1.0–3.7 million days/ha, respectively.
Studies have shown that the lowest PPF value for the «Batya» variety was 2.0 g/m²/day in 2020 when sown during a late period and that the maximum value was 4.2 g/m²/day in 2018 when sown at the end of May. The lowest leaf activity in «Khabarovskiy Yubilyar» (3.4 g/m/day) was also observed in plants from the late sowing period in 2020. In terms of the net productivity of photosynthesis, «Khabarovskiy Yubilyar» was on average two times higher than «Batya».

The generated photosynthetic activity determined the productivity of plants (table 3).

**Table 3.** Statistical analysis of the main indicators of soybean productivity for the varieties «Batya» and «Khabarovskiy Yubilyar» at different sowing dates.

|            | 1    | 2    | 3    | 4    | 5    | 6    | X_{cp} ±ΔX_{cp} | V.% | LSD_{0.5} |
|------------|------|------|------|------|------|------|----------------|-----|-----------|
| **x1**     |      |      |      |      |      |      |                |     |           |
| «Batya»    |      |      |      |      |      |      |                |     |           |
| 2018       | 3.92 | 2.66 | 2.20 |      |      |      | 3±2.2          | 30.0| 0.49      |
| 2019       | 2.70 | 2.80 | 2.96 | 3.08 | 2.68 | 2.52 | 3±0.21         | 7.3 | 0.35      |
| 2020       | 3.01 | 3.24 | 3.48 | 3.52 | 3.83 | 2.81 | 3±0.39         | 11.2| 0.35      |
| y1         |      |      |      |      |      |      |                |     |           |
| «Khabarovskiy Yubilyar» |      |      |      |      |      |      |                |     |           |
| 2018       | 22   | 15   | 11   | -    | -    | -    | 16±5           | 34.8|           |
| 2019       | 27   | 21   | 20   | 21   | 16   | 14   | 20±5           | 22.9|           |
| 2020       | 14.1 | 14.9 | 16.6 | 17.4 | 18.5 | 11.9 | 16±2           | 15.5|           |
| y2         |      |      |      |      |      |      |                |     |           |
| «Batya»    |      |      |      |      |      |      |                |     |           |
| 2018       | 2018 | 213  | 185  | 183  |      |      | 194±17         | 8.7 |           |
| 2019       | 218  | 214  | 224  | 220  | 216  | 210  | 217±5          | 2.2 |           |
| 2020       | 217  | 212  | 222  | 217  | 204  | 217  | 179±20         | 8.0 |           |
| y3         |      |      |      |      |      |      |                |     |           |
| «Khabarovskiy Yubilyar» |      |      |      |      |      |      |                |     |           |
| 2018       | 21   | 19   | 14   | -    | -    | -    | 18±4           | 20.0|           |
| 2019       | 37   | 33   | 29   | 25   | 21   | 19   | 27±7           | 25.5|           |
| 2020       | 23.0 | 29.3 | 31.9 | 30.7 | 30.5 | 24.4 | 27±7           | 25.7|           |
| y4         |      |      |      |      |      |      |                |     |           |
| «Batya»    |      |      |      |      |      |      |                |     |           |
| 2018       | 3.78 | 2.63 | 2.16 | -    | -    | -    | 3±2            | 29.2| 0.47      |
| 2019       | 3.17 | 3.35 | 3.24 | 3.26 | 3.0  | 2.58 | 3±0.3          | 9.0 | 0.40      |
| 2020       | 3.89 | 4.79 | 4.89 | 4.3  | 4.27 | 3.29 | 4±62           | 13.98| 0.4       |
| y5         |      |      |      |      |      |      |                |     |           |
| «Khabarovskiy Yubilyar» |      |      |      |      |      |      |                |     |           |
| 2018       | 203  | 181  | 178  | -    | -    | -    | 187±13         | 7.3 |           |
| 2019       | 186  | 184  | 184  | 190  | 186  | 194  | 187±4          | 2.1 |           |
| 2020       | 215  | 204  | 200  | 192  | 190  | 212  | 202±11         | 5.05|           |

Correlation analysis revealed that the most significant factor which determined the level of biological productivity was the leaf area. The influence of this factor was 92.3% and by 77.3% depends on the photosynthetic potential (table 4).

**Table 4.** Correlation coefficients.

| x1 «Batya» | x2 «Batya» | x3 «Batya» | x1 «Khabarovskiy Yubilyar» | x2 «Khabarovskiy Yubilyar» | x3 «Khabarovskiy Yubilyar» |
|------------|------------|------------|----------------------------|----------------------------|----------------------------|
| y1         | 0.99       | 0.92       | 0.55                       | 0.92                       | 0.84                       | 0.53                       |
| y2         | 0.78       | 0.78       | 0.67                       | 0.85                       | 0.77                       | 0.40                       |
| y3         | 0.22       | 0.25       | 0.03                       | 0.19                       | 0.33                       | 0.09                       |
| y4         | 0.13       | 0.04       | 0.04                       | 0.42                       | 0.36                       | 0.16                       |
| y5         | 0.25       | 0.15       | 0.1                        | 0.45                       | 0.59                       | 0.28                       |
| y6         | 0.05       | 0.05       | -0.03                      | 0.46                       | 0.38                       | 0.31                       |
| y7         | -0.17      | -0.06      | -0.27                      | 0.14                       | -0.03                      | 0.09                       |
For a quantitative assessment of the most variable characteristics, we constructed regression equations for the varieties «Batya» (1) and «Khabarovskiy Yubilyar» (2) describing the yield from the leaf surface area and photosynthetic potential. The determination coefficients were 0.98 and 0.84, respectively:

\[
X_3 = 2.51 - 0.02\cdot y_4 + 1.25\cdot y_3
\]

\[
X_3 = 0.95 - 0.02\cdot y_4 + 1.25\cdot y_3
\]

4. Conclusions
The optimal conditions for leaf development and function in soybean occurred in plants sown in May; plants sown at later dates showed that leaf area decreased by 6–36% and 11–27% in «Batya» and «Khabarovskiy Yubilyar», respectively. In terms of net photosynthetic productivity, «Khabarovskiy Yubilyar» was on average two times higher than «Batya». Studies have shown that the lowest PPF value for the «Batya» variety was 2.0 g/m²/day when sown during a late period and that the maximum value was 4.2 g/m²/day when sown at the end of May. The lowest leaf activity in «Khabarovskiy Yubilyar» (3.4 g/m²/day) was also observed in plants from a late sowing period. Correlation analysis showed that the most significant factor which determined the level of biological productivity was the leaf area. The influence of this factor was 92.3% and by 77.3% depends on the photosynthetic potential.

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