Assessment of photosynthetic productivity of new perennial forage crops in forest-steppe conditions of Western Siberia

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Abstract. The article presents the results of six years of experience in comparative evaluation of perennial forage crops (Sida hermaphrodita Rusby., Silphium perfoliatum L., Polygonum divaricatum L., Polygonum weyrichii Fr. Schmidt, Helianthus tuberosus L., Raphonticum carthamoides (Willd.), Symphytum asperum Lep., Urtica dioica L., Isatis tinctoria L., Rumex tianschanicus L. × Rumex patientia L.) on parameters of photosynthetic activity and dry matter yield in the forest-steppe conditions of Western Siberia. These crops are characterized by environmental plasticity, longevity (up to 25 years), high productivity (30-100 t/ha of green mass). And they have a versatile economic use. The experiment's purpose is to assess the potential of crop cultivation and recommend species for inclusion in the regional cropping system. It was found that the largest area indicators of the assimilable apparatus (131.4-149.3 thousand m² / ha) and photosynthetic potential (4.5–4.6 million m² day/ha) were in S. hermaphrodita and S. perfoliatum crops, which exceeded the maize values by 1.2–2.4 times. A significant increase in leaf area in these crops contributed to a 23% decrease in net photosynthesis productivity compared to maize. By collecting dry matter for two mowings, these crops surpassed maize by 65-85% with a relatively high indicator of EER PAR (1.2 - 1.4%).

1. Introduction
Modern agriculture should be based on the biological balance in agro-landscape systems. This means that without productivity reducing and agricultural productivity, to pursue a policy of environment protection through environment conservancy and optimal control of cultivated lands [1, 2]. The key link in agro-landscape systems should be perennial grasses that actively participate not only in the conservation but also in the multiplication of organic matter in the biosphere. Perennial grasses cultivation for the needs of fodder cropping makes it possible to obtain not only a good feed for livestock animals in terms of its nutritive properties but also to prevent soil erosion, improve its structure, land fertility and phytosanitary condition due to reproducible natural resources (photosynthesis and symbiotic nitrogen fixation) [1].

Photosynthesis of plants is assigned a major role in the productivity formation since it is the only source of organic matter formation. The photosynthetic activity of crops includes the following parameters: leaf surface area, photosynthetic potential (PP) of the crop, net photosynthesis productivity (NPP), and the PAR utilization quotient (EER PAR). These parameters can be used to state assess of the agroecosystem, productivity, forecast yields, and the effectiveness of the cultural operations.
Each crop has its unique features for the functioning of the leaf surface, the photosynthetic rate, and productivity under certain environmental conditions. In Western Siberia, where a short growing season is typical, it is important to cultivate such crops and varieties that can form a powerful assimilation surface of leaves with a long period of functioning in a relatively short period and can fully realize their productive potential in these conditions.

For the conditions of the forest-steppe of Western Siberia are considered promising of perennial forage crops: *Sida hermaphrodita* Rusby, *Silphium perfoliatum* L., *Polygonum divaricatum* L., *Polygonum weyrichii* Fr. Schmidt, *Helianthus tuberosus* L., *Rhaponticum carthamoides* (Willd.), *Symphytum asperum* Lep., *Urtica dioica* L., *Isatis tinctoria* L., *Rumex tianschanicus* × *Rumex patientia* L. These crops are resistant to pathogenic organisms, have ecological plasticity and high productivity potential (30-100 t/ha of green mass), and are used not only in fodder cropping but also in the food industry, beekeeping, medicine, land reclamation and recultivation [3-6]. They differ in significant longevity of practical use from 8 (*U. Dioica*) up to 25 (*S. hermaphrodita*) years, except for *I. tinctoria*, the duration of use of which does not exceed two years [3].

*S. hermaphrodita*, *S. perfoliatum*, *H. tuberosus*, *P. divaricatum*, and *R. tianschanicus* × *R. patientia* are alternative maize crops for the production of biofuel and biogas since they can form powerful biomass during the growing season, while not requiring large expenditures on soil preparation and weed and pest control [7, 8]. They are used as phytomeliorants and phytoremediants to restore the structure of the soil layer and remove toxic salts. They are recommended for cultivation on degraded soils with salt content and contaminated with heavy metals, where they can form not only a high yield of biomass but also reduce the content of these metals in the soil [5, 9].

*R. carthamoides*, *S. asperum*, and *U. dioica* are natural sources of vitamins, ash constituents, and biologically active substances, including steroids [6, 11, 12]. Therefore, these crops are recommended to include in the diets of livestock animals and birds in the form of highly effective feed additives for therapeutic purposes and to increase their productive and reproductive functions.

These forage crops, due to the formation of significant aboveground biomass, their versatile economic properties, and environmental advantages of cultivation can fit well into the modern system of land husbandry.

This article's purpose is to provide an assessment of the photosynthetic potential and productivity of new perennial forage crops in Western Siberia to expand the species diversity of forage crops in this region.

### 2. Materials and methods

The experiment was conducted on the experimental field of the Omsk State Agrarian University, which is located in the forest-steppe of Western Siberia (Omsk: 54.94 N; 73.36 E). The climate of Omsk is continental, with an average annual temperature of 1.7 °C and average annual precipitation of 400 mm. The soil cover of the site is typical for this zone – meadow chernozem soil. Agrotechnical characteristics of the surface soil are humus 3.4%, pH 6.7-7.4, the content of N-NO_3 -12 mg, P_2O_5 -284 mg, and K_2O -225 mg per 1 kg of soil.

The research object was 10 species of perennial forage crops of silage direction: *Sida hermaphrodita*, *Silphium perfoliatum*, *Polygonum divaricatum*, *Polygonum weyrichii*, *Helianthus tuberosus*, *Rhaponticum carthamoides*, *Symphytum asperum*, *Urtica dioica*, *Isatis tinctoria*, *Rumex tianschanicus* × *Rumex patientia*. These crops were sown in 4-fold repetition in early May, with a row spacing of 70 cm and a seeding rate of 0.5-2.0 million germinated seeds/ha. Once in two years, *I. tinctoria* was sown in an ordinary (after 15 cm) way and the seeding rate was 3.5 million pieces of seeds/ha. As a control, we used annual maize crops with a seeding rate of 60 thousand plants/ha. The accounting area of plots is 25 m². The predecessor is black fallow. Agricultural technology in the experiment is generally accepted for the forest-steppe of Western Siberia.

For six years during the growing season, studies were conducted on the photosynthetic activity of crops in the first and second mowing. When determining the leaf area, we used the die-cut method [13], photosynthetic potential, and net photosynthesis productivity using the Nichiporovich calculation.
method [14], and the PAR utilization factor (EER PAR) using Tooming method [15]. Statistical manipulation of experimental data was performed using the Dospekhov method [16].

In the first year one mowing and subsequent years two mowing were performed when the plants reached mowing ripeness (blooming period). Maize was harvested once during the growing season during the phase of milky-waxy ripeness of the cobs. Accounting for the fresh yield was carried out continuously. On the day of harvest, the content of a dry basis was determined in the CCU "Agricultural and Technological research". To do this was selected 10 plants, which were cut and crushed to less than 1 cm. Then a sample was formed weighing from 1 kg from which three portions weighing 100 g were selected. Each portion dried at a temperature of 105°C to constant mass.

Hydro-meteorological conditions in the research years had differences in heat and moisture availability but generally corresponded to the climate of the forest-steppe zone of Western Siberia.

3. Results and discussion

According to the data obtained, it follows that the studied forage crops differ in the length of the growing period and the earliest ready for mowing were *R. carthamoides*, *R. tianschanicus*, *R. patientia*, and *I. tinctoria*, whose period of crop formation on average over the years of observations in the first mowing was 42-48 and 35-51 days in the second (table 1). Later than all mowing ripeness in the first mowing reached plants *S. hermaphrodita*, *S. perfoliatum*, *P. divaricatun*, *H. tuberosus*, and *U. dioica* 58-64 days after the beginning of vegetation renewal in spring. In the second mowing were delayed with harvesting *H. tuberosus*, *S. hermaphrodita*, and *S. perfoliatum*, the period of crop formation was 65-69 days.

Table 1. Indicators of photosynthetic activity and forage crops productivity (on average for six years)

| Cropper                  | Period of the crop formation, days | Absolutely dry basis, t/ha | The leaves area, thousand m²/ha | PP, million m²/ha | NPP, g/m² * day |
|--------------------------|------------------------------------|-----------------------------|---------------------------------|-------------------|-----------------|
| Zea mays L.              | 110 - 10 - a                        | 5.7 - 62.1 - a              | 3.4 - 1.7 - a                   |                   |                 |
| *Sida hermaphrodita*     | 64 66 a b                          | 5.7 3.7 3.7                 | 131.4 69.6 4.6 1.8 1.3 2.0      |                   |                 |
| *Silphium perfoliatum* L.| 62 65 b a                          | 6.2 4.4 4.4                 | 149.3 69.6 4.6 2.2 1.3 1.9      |                   |                 |
| *Rumex tianschanicus* L. | 48 45 a b                          | 5.6 2.9 2.9                 | 59.3 26.3 1.4 0.6 3.9 4.8       |                   |                 |
| *Polygonum divaricatun* L.| 58 59 a b                          | 4.0 3.4 3.4                 | 125.3 59.6 3.5 1.8 1.1 1.9      |                   |                 |
| *Polygonum weyrichii* Fr. Schmidt | 54 64 a b                          | 3.2 2.1 2.1                 | 91.2 42.7 2.4 1.4 1.3 1.6      |                   |                 |
| *Helianthus tuberosus* L.| 52 69 b a                          | 5.1 2.0 2.0                 | 59.3 35.1 1.5 1.2 3.4 1.7      |                   |                 |
| *Rhaponticum carthamoides* (Willd.) | 42 51 a b                          | 2.5 1.8 1.8                 | 45.7 29.4 0.9 0.8 2.6 2.4      |                   |                 |
| *Symphytum asperum* Lep. | 53 56 b a                          | 4.0 3.2 3.2                 | 115.1 70.3 3.1 1.9 1.3 1.6      |                   |                 |
| *Urtica dioica* L.       | 60 60 b a                          | 2.9 2.0 2.0                 | 78.7 31.2 2.3 0.9 1.3 2.1      |                   |                 |
| *Isatis tinctoria* L.    | 45 35 a b                          | 2.2 1.3 1.3                 | 28.1 10.0 0.6 0.2 3.4 7.1      |                   |                 |

| a | First mowing     |
| b | Second mowing   |

The studied forage crops were mostly distinguished by the photosynthetic apparatus formation, which exceeded the standard value of high-yielding agro phytocoenosis 50 thousand m²/ha [14]. So, by the time of harvesting the first mowing, the largest leaves area (91.2-149.3 thousand m² / ha) was observed in *S. hermaphrodita*, *S. perfoliatum*, *P. divaricatun*, *P. weyrichii* and *S. asperum* crops, which
exceeded the value of the maize leaf area by 1.5-2.4 times. This increase in leaf area in these crops is due to increased leaf coverage. The share of leaves in the crop structure of the green mass of the first mowing was 42.9-58.9%, which exceeded the values of the control culture by 1.4-2.0 times. The leaf surface area of R. tianschanicus × R. patientia, H. tuberosus, and U. dioica reached 59.3-78.7 thousand m²/ha by the end of the vegetation period of the first mowing, which corresponded to the leaf surface level of maize - 62.1 thousand m²/ha.

In the second mowing, crops formed a leaf surface area of 35.7–64.4% less than in the first mowing but remained, in general, this indicator high 53.2–70.3 thousand m²/ha in such crops as S. hermaphrodita, S. perfoliatum, P. divaricatun, and S. asperum. In the first and second mowing was the smallest leaf area in I. tinctoria plants -28.1 and 10.0 thousand m²/ha, respectively. The decrease in leaf area during the second mowing formation is explained by a significant decrease in the development rate of the leaf surface of grasses.

Photosynthetic potential (PP) of crops characterizes the total leaves area and the duration of their functioning during the crop formation. This indicator is determined by morphological and biological features of the cropper and environmental growth conditions [17]. The optimal value of the PP in the formation of a dry biomass crop should be in the range of 1.5-2.0 million m² day/ha [14].

The highest rate of PP in the first mowing was observed in the crops of S. perfoliatum and S. hermaphrodita, which averaged 4.6 and 4.2 million m² day/ha, and exceeded the maize values by 23-35%. Crops of R. carthamoides and I. tinctoria had a minimum PP of 0.6-0.9 million m² day/ha, which is explained by the non-continuous operation of the assimilation surface of leaves as a result of a short growing season. The remaining crops had a higher or lower PP than the optimal value for generating a high yield level. The PP crops of the second mowing were significantly reduced by 2.0-2.5 times compared to the first in the following croppers: U. dioica, S. perfoliatum, S. hermaphrodita, R. tianschanicus, R. patientia, and P. divaricatun.

The net productivity of photosynthesis (NPP) determines the intensity of work leaves and represents the amount of dry biomass synthesized by a leaf surface unit over a particular period [14]. This indicator is very dependent on the development features of the photosynthetic apparatus of plants, the illumination of crops, and technological methods of cultivation. Before harvesting the first mowing, it was noted that the highest NPP is typical for croppers that recorded a short period of crop formation, the smallest area of the assimilating apparatus, and photosynthetic potential. Thus, the NPP on crops of R. tianschanicus × R. patientia, H. tuberosus, R. carthamoides, and I. tinctoria was 2.6–3.9 g / m²*days. This is because these crops had a lower proportion of leaves in their structure (36.2–37.7%), and therefore, it was less shadowing of the lower leaves in the herbage. In the second mowing, the NPP increased 1.5-2.1 times compared to the first mowing in such crops as S. perfoliatum, S. hermaphrodita, P. divaricatun, H. tuberosus, U. dioica, and I. tinctoria. The second mowing of perennial grasses was formed under less favorable conditions for providing plants with moisture and heat, which affected the growth and development of their leaves. As a result, the herbage was formed with a smaller area of the assimilating surface, but with an optimal arrangement of leaves in height and their orientation about light.

The forage crops productivity determines the efficiency of their photosynthetic activity during the growing season. The collection of absolutely dry matter in total for two mowing crops of S. perfoliatum, S. hermaphrodita, R. tianschanicus, R. patientia, P. divaricatun, S. asperum, and H. tuberosus averaged 7.1–10.6 t/ha, which exceeded the maize value by 26-85%. The remaining crops had dry matter productivity slightly lower or at the maize level, except for I. tinctoria, which had a completely dry matter yield that was 38% less than control. Correlation analysis showed that the dry matter productivity in crops was determined by the size of the photosynthetic apparatus (r=0.7±0.06) and the photosynthetic potential (r=0.81±0.04).

To estimate the amount of storage power in the resulting crop in comparison with the received an indicator is used EER PAR. The value of the PAR utilization coefficient is judged on the photosynthetic apparatus efficiency of agro phytocoenosis. Crops with EER PAR of 0.5-1.5% are considered to have a low level of PAR use, medium-1.5-3.0 and high-3.0–5.0% [14]. Perennial forage
crops absorbed solar energy in different ways and converted it into a crop. Thus, the EER PAR in the studied crops varied on average from 0.7 to 1.9% (figure 1).

**Figure 1.** EER PAR of croppers.: 1. Zea mays 2. Sida hermaphrodita 3. Silphium perfoliatum 4. Rumex tianschanicus × Rumex patientia 5. Polygonum divaricatun 6. Polygonum weyrichii 7. Helianthus tuberosus 8. Rhaponticum carthamoides 9. Symphytum asperum 10. Urtica dioica 11. Isatis tinctoria

High EER PAR indicators (1.2-1.4%) were observed on crops of *S. perfoliatum, S. asperum, S. hermaphrodita, H. tuberosus*, and the most effective use of PAR was recorded on the herbage of *R. tianschanicus × R. patientia* – 1.9%. Despite such a high level of the FAR use, received for these crops, this indicator can be increased by using scientific-based elements of intensive cultivation technology. At the same time, the potential of the forest–steppe zone of Western Siberia for the arrival of solar output (39-41 MJ/m² per year) and heat (the sum of temperatures above 10 °C-1600 -2050 °C) is very significant. The correlation analysis of the relationship between productivity and EER PAR herbage showed a strong positive relationship between the marked parameters-\(r= 0.78 \pm 0.18\).

### 4. Conclusion

Photosynthetic activity analysis shows that such cultures as *S. hermaphrodita, S. perfoliatum, P. divaricatun, and S. asperum* form a powerful photosynthetic apparatus in the first mowing (115.1-149.3 thousand m²/ha), which exceeds the area of maize leaves by 1.8-2.4 times. By the second mowing, the leaf area decreases by 35.7-64.4% but remains quite high-53.2-70.3 thousand m²/ha. *S. perfoliatum* and *S. hermaphrodita* crops in the first moving have the highest value of PP (4.6 and 4.2 million m² day/ha), which by the end of the second mowing due to the reduction of the leaf area decreases by 2.0-2.3 times. Significant indicators of photosynthetic activity in *S. perfoliatum, S. hermaphrodita, R. tianschanicus, R. patientia, P. divaricatun, S. asperum, and H. tuberosus* crops determine a high yield of dry matter, which is 7.1–10.6 t/ha or 26-85% higher than in maize on average for two mowing operations. The assimilation activity efficiency of these crops is confirmed by the high EER PAR 1.2-1.9%. A strong direct relationship between the parameters of the photosynthetic activity of crops and the yield of dry matter indicates the possibility of regulating the production processes of herbage by affecting plant photosynthesis. Therefore, the inclusion in the farming system of forest-steppe of Western Siberia high-yielding perennial forage crops: *S. perfoliatum, S. asperum, S. hermaphrodita, H. tuberosus, R. tianschanicus × R. patientia,P. divaricatun* will stabilize not only fodder cropping but also the ecological balance in agro-landscape systems of the region.

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