Willow communities, optimal absorption of carbon dioxide from the atmosphere

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Abstract. High biological productivity of willow communities contributes to the effective performance of carbon dioxide absorption in photosynthesis. In natural communities, shrub willows exhibit a better effect on carbon dioxide balance: the amount of absorbed gas significantly exceeds its emission. Deciduous willows are able to fulfill the same condition, but only when grown in plantations. For the effective absorption of carbon dioxide, willow communities should meet the following parameters depending on the soil conditions. A one-year phytomass growth of axial shoots (in terms of absolutely dry matter) should be more than 3.11 tons/hectare·year⁻¹ on rich soils. This condition is fully met by the Salix dasyclados and S. viminalis communities. When growing on poor soils, annual phytomass growth of axial shoots of more than 0.93 tons/hectare·year⁻¹ is sufficient, which is noted in the communities of S. purpurea. The annual increase in phytomass of axial shoots should be more than 2.48 tons/hectare·year⁻¹ when growing on swampy soils. S. dasyclados and S. viminalis are the most suitable for plantation cultivation. These willow species perform the raw material function in the most effective way and, along with this, absorb carbon dioxide from the atmosphere in the greatest amount.

1. Introduction

Currently, the global task is to find methods for reducing the concentration of carbon dioxide in the atmosphere. One solution is the use of plant communities that can assimilate carbon dioxide in photosynthesis [1], including forest ones. The amount of absorbed carbon dioxide is directly proportional to the formed phytomass. In connection with this, the task is more actively performed by the plants with high energy of growth. A significant amount of research is devoted to research of the effect of plant organisms on the gas composition of the atmosphere. There is a positive effect on the assimilation of carbon dioxide by agricultural crops [2, 3], as well as by forests [4-6]. The high absorption capacity is observed in willow natural communities and willow plantations [6-8].

The communities formed by plants of the genus Salix are located in the floodplains of rivers and other habitats with high soil moisture. In these places they primarily perform the function of protecting water bodies. The impact on the gas composition of the atmosphere increases their environmental value. In central Russia, the plants of the family Salicaceae exhibit the maximum growth energy among the woody trees, and at a young age - of the genus Salix [9].
willow plantations with annual cuttings grown on rich soil (leached chernozem) in the Voronezh region [10] hectares showed that S. dasyclados is the most productive. Its total aboveground phytomass reaches 15.73 tons/hectare during every utilization cycle in terms of absolutely dry substance. Similar productivity (12.75 tons/hectare) was noted in S. viminalis and the minimal one (5.74 tons/hectare) - in S. x palustris.

The purpose of this study is to estimate the amount of carbon dioxide taken from the atmosphere during the formation of phytomass of willow communities and to determine the parameters of willow cenoses which are the most effective for solving this problem.

2. Methods and materials

Initially, standard methods in the forest industry [11] established the amount of stem wood in cubic meters to assess the productivity of willow communities. The amount of wood accumulation for one year was calculated (the current annual increase) by dividing the amount of wood at the observed age by the number of years between observations in order to ensure the comparability of results for plants of different ages.

The amount of assimilated carbon dioxide was determined according to the methods [12-14], consistent with the methodology for estimating carbon deposition, approved by the Intergovernmental Panel on Climate Change. The essence of the technique is reduced to recalculating the stock of wood from cubic meters to tons (based on the density of wood, which is 0.4 for willow) and calculating (based on age-dependent conversion factors) the amount of carbon dioxide assimilation.

The studies were carried out at a time, in 2017. Measurements were made of natural and artificial communities of different ages under the same weather conditions.

We studied the following species of willow in natural communities: S. fragilis, S. viminalis, S. triandra, S. purpurea, and S. cinerea. The communities of S. fragilis studied by us represent an age range from middle-aged (15 years) to overripe (65 years) stands. For S. fragilis, 11 communities differing in age were studied. The research was conducted in the floodplain of the river Don. Geographical coordinates of the studied S. fragilis communities: 51.12° N, 39.14° E. Geographical coordinates of S. viminalis, S. triandra, S. purpurea, and S. cinerea communities: 51.41° N, 39.02° E.

The following willow taxa were studied on the plantations: S. dasyclados; S. viminalis; S. purpurea; S. x acuminate; S. triandra; S. caspica; S. x americana; S. schwerinii; S. x palustris. Geographical coordinates of willow plantation: 51.43° N, 38.57° E.

3. Results and discussion

High biological productivity of willow communities contributes to the effective performance of carbon dioxide absorption in photosynthesis. The manifestation of this function will be illustrated with the example of wild willow trees in the floodplain of the Don River, where their maximum productivity is noted, as well as on the example of willow plantations. In the floodplains, the maximum area falls on the stands of S. fragilis and tangled vegetation formed by S. viminalis, S. triandra, S. purpurea, S. cinerea.

The studied S. fragilis communities represent the age range from middle-aged (15 years) to over-mature (65 years) tree stands. During the period of vital activity, deciduous willow trees accumulate significant phytomass. However, their growth energy chtereenges with age, and detritus is accumulated as a result of tree death (table 1).
Table 1. The chectarenge in phytomass and detritus volume with the increase of *S. fragilis* tree stand ages.

| Age, years | In the observed age, tons·hectare\(^{-1}\) | Annual growth, tons·hectare\(^{-1}\)·year\(^{-1}\) | In the observed age, tons·hectare\(^{-1}\) | Annual growth, tons·hectare\(^{-1}\)·year\(^{-1}\) |
|------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 15         | 22.8 ± 1.47                                   | 1.47                                           | 0.4 ± 0.01                                    | 0.03                                          |
| 20         | 32.1 ± 1.55                                   | 1.55                                           | 1.6 ± 0.03                                    | 0.08                                          |
| 25         | 40.3 ± 0.73                                   | 1.56                                           | 4.0 ± 0.07                                    | 0.16                                          |
| 30         | 45.6 ± 0.82                                   | 1.47                                           | 6.8 ± 0.12                                    | 0.23                                          |
| 35         | 47.3 ± 0.85                                   | 1.31                                           | 11.6 ± 0.21                                   | 0.33                                          |
| 40         | 50.8 ± 0.91                                   | 1.23                                           | 14.4 ± 0.26                                   | 0.36                                          |
| 45         | 50.8 ± 0.91                                   | 1.09                                           | 18.4 ± 0.33                                   | 0.41                                          |
| 50         | 60.7 ± 1.09                                   | 1.17                                           | 14.4 ± 0.26                                   | 0.29                                          |
| 55         | 51.4 ± 0.93                                   | 0.90                                           | 14.8 ± 0.27                                   | 0.27                                          |
| 60         | 39.1 ± 0.70                                   | 0.63                                           | 15.6 ± 0.28                                   | 0.26                                          |
| 65         | 29.8 ± 0.54                                   | 0.44                                           | 14.0 ± 0.25                                   | 0.22                                          |

The maximum increase in phytomass (1.47 tons·hectare\(^{-1}\)·year\(^{-1}\)) is observed in 30-year-old stands, after which the growth rate decreases. There is a significant dying-off of trees and accumulation of arboreal detritus in communities already from the age of 25. The accumulation of phytomass occurs at a slower rate in stands which are older than 30 years, but the rates of detritus accumulation increase. This circumstance affects the amount of carbon dioxide absorption during the formation of phytomass and its emission during detritus decomposition at different age of trees (table 2).

Table 2. The amount of carbon dioxide absorbed by one-year increment and released during detritus decomposition in the stands of *S. fragilis*, tons·hectare\(^{-1}\)·year\(^{-1}\).

| Age, years | CO\(_2\) by the components of phytomass growth | CO\(_2\) of detritus |
|------------|-----------------------------------------------|---------------------|
|            | Trunk Brances Roots Total                      |                     |
| 15         | 1.87 0.37 0.39 2.63 0.05                       |                     |
| 20         | 1.98 0.40 0.42 2.80 0.14                       |                     |
| 25         | 1.99 0.40 0.42 2.81 0.29                       |                     |
| 30         | 1.87 0.37 0.39 2.63 0.41                       |                     |
| 35         | 1.67 0.33 0.35 2.35 0.60                       |                     |
| 40         | 1.57 0.31 0.33 2.21 0.65                       |                     |
| 45         | 1.90 0.28 0.29 1.96 0.74                       |                     |
| 50         | 1.50 0.30 0.31 2.11 0.52                       |                     |
| 55         | 1.15 0.23 0.24 1.62 0.48                       |                     |
| 60         | 0.80 0.16 0.17 1.13 0.47                       |                     |
| 65         | 0.56 0.11 0.12 0.79 0.39                       |                     |

The maximum amount of carbon dioxide (2.81 tons·hectare\(^{-1}\)·year\(^{-1}\)) of *S. fragilis* stands is absorbed at the age of 25. A significant impact on the carbon dioxide balance in the territory occupied by plant communities is exerted by its emission as a result of soil respiration, decomposition of tree detritus and forest litter. The maximum shectarere of emissions is taken by soil respiration. Dry wood accumulates with forest age, the decomposition of which produces a significant proportion of carbon dioxide. Emission during decomposition of leaf mass is proportional to the total phytomass of the
stand. The carbon dioxide balance in the stands of *S. fragilis* is the difference between its emission and absorption. It is shown in figure 1.

The emission value exceeds the absorption of carbon dioxide during the formation of phytomass for all the surveyed stands of *S. fragilis*. The difference between these values increases with the age of tree stands, which is mainly due to the accumulation of dead wood. This circumstance indicates the need for timely removal of dry stock in the process of sanitary and recreational activities.

![Figure 1. Cheetarenging balance of carbon dioxide with forest age of *S. fragilis*, tons·hectare⁻¹·year⁻¹.](image)

The shrub willows (for example *S. viminalis*, *S. triandra*, *S. purpurea*, and *S. cinerea*) differ from deciduous species (for example *S. fragilis*) by increased growth energy at a young age. The annual growth of phytomass in their natural communities reaches 4.9-11.3 tons·hectare⁻¹·year⁻¹ depending on the willow species. This circumstance is greater seen in the shrub communities in the amount of carbon dioxide assimilation (table 3).

| Willow species | Phytomass | Absorbed CO₂ | Emission of CO₂ | Balance of CO₂ |
|----------------|-----------|--------------|----------------|---------------|
| *S. viminalis*  | 11.3 ± 0.19 | 20.3         | 7.9            | -12.4         |
| *S. triandra*   | 8.5 ± 0.14  | 15.3         | 3.7            | -11.4         |
| *S. purpurea*   | 7.3 ± 0.12  | 13.1         | 3.4            | -9.7          |
| *S. cinerea*    | 4.9 ± 0.08  | 8.8          | 6.6            | -2.2          |

Among shrub willows, the maximum amount of absorbed carbon dioxide (20.3 tons·hectare⁻¹·year⁻¹) was observed when one-year increment in *S. viminalis* community was formed. The emission of carbon dioxide depends (to the maximum extent) on the magnitude of the soil respiration. The communities of *S. viminalis* grow on the most fertile soils; the communities of *S. purpurea* grow on the less fertile ones. This fact hectares caused significant differences in the amount of emissions. Since *S. viminalis* hectares maximum growth energy in the series of the studied wild willow species, it affects the carbon dioxide balance most significantly (even in rich soil). The amount of carbon dioxide decreases each year by 12.4 tons·hectare⁻¹ with its growth.
The plantations have the ability to manage the production of the best genotypes in optimal conditions. Comparison of the productivity of planetary reserves and annual turnover enables to identify the maximum phytomass productivity (18.84 tons·hectare⁻¹·year⁻¹ in terms of absolutely dry substance) for *S. dasyclados* and minimum (6.84 tons·hectare⁻¹·year⁻¹) – for *S. x palustris*. The high productivity (from 9.72 to 15.24 tons·hectare⁻¹·year⁻¹) is specific to *S. viminalis, S.x acuminata, S. triandra, S. purpurea, S. caspica,* and *S. x americana* plantations. A pattern found in natural willow communities is also seen in plantations. The extent is shrub willows (in particular, *S. dasyclados, S. viminalis, S. x acuminata, S. triandra, S. purpurea, S. caspica,* and *S. x americana*) exceed deciduous willows (in particular, *S. x palustris,* which is a hybrid of *S. alba* and *S. fragilis*) in growth energies.

While growing on the same soil, the balance of carbon dioxide is most significantly affected by the growth energy of the cultivar. The high growth energy willow species and hybrids absorb the maximum amount of carbon dioxide. The emission of this gas in the territory occupied by them is also greater the extent with the growth of willows of low growth energy. It is associated with the number of annually rotting detritus. On leached chernozem, the maximum amount of carbon dioxide absorption is observed on *S. dasyclados* plantations (33.9 tons·hectare⁻¹·year⁻¹) (table 4).

**Table 4.** Calculation of carbon dioxide balance on willow plantations with one-year cutting felling, tons·hectare⁻¹·year⁻¹.

| Species, Willow Hybrid | Absorbed CO₂, tons·hectare⁻¹·year⁻¹ | Emission of CO₂, tons·hectare⁻¹·year⁻¹ | Balance of CO₂, tons·hectare⁻¹·year⁻¹ |
|-----------------------|------------------------------------|---------------------------------------|--------------------------------------|
| *S. dasyclados*       | 33.9                               | 14.18                                 | -19.73                               |
| *S. viminalis*        | 27.4                               | 12.38                                 | -15.05                               |
| *S. purpurea*         | 26.5                               | 10.58                                 | -15.99                               |
| *S. x acuminata*      | 25.4                               | 11.84                                 | -13.65                               |
| *S. triandra*         | 25.3                               | 10.58                                 | -14.69                               |
| *S. caspica*          | 23.3                               | 9.50                                  | 13.83                                |
| *S. x americana*      | 20.1                               | 9.14                                  | -10.95                               |
| *S. schwerinii*       | 17.5                               | 9.50                                  | -8.00                                |
| *S. x palustris*      | 12.3                               | 7.52                                  | -4.79                                |

More favorable balance of dioxide is noted on the *S. dasyclados* plantation and the least favorable – on the *S. x palustris* plantation in proportion to the magnitude of absorption and emission. This confirms the hypothesis of the feasibility of plantation cultivation using more productive cultivars.

The fast-growing willow species are more effective in terms of absorbed carbon dioxide both in natural communities and on plantations. In this case, a general pattern can be traced. Shrub willows stand out for the better in terms of the growth energy and the effect on the amount of carbon dioxide (figure 2).

The deciduous willows are able to absorb carbon dioxide by an amount exceeding its emission only under the most favorable conditions, for example, in plantation growing on rich soil. Shrub biomorphs are the most productive among the willows, and, accordingly, hectare the most beneficial effect on the carbon dioxide balance, both in natural communities and on plantations of *S. dasyclados* and *S. viminalis.*
4. Conclusion

The following conclusions can be drawn on the basis of the above data. The shrub willows hectareve a better effect on carbon dioxide balance in natural communities: the amount of absorbed gas significantly exceeds its emission. Deciduous willows are able to fulfill the same condition, but only when they are grown on plantations.

Willow communities should meet the following parameters depending on the soil conditions for the carbon dioxide effective absorption. A one-year phytomass growth of axial shoots (in terms of absolutely dry matter) should be more thectaren 3.11 tons-hectare⁻¹-year⁻¹ on rich soils. This condition is fully met by the S. dasyclados and S. viminalis communities. When growing on poor soils, annual phytomass growth of axial shoots of more thectaren 0.93 tons-hectare⁻¹-year⁻¹ is sufficient, which is noted in the communities of S. purpurea. The annual increase in phytomass of axial shoots should be more 2.48 tons-hectare⁻¹-year⁻¹ when growing on swampy soils. S. dasyclados and S. viminalis are the most suitable for plantation cultivation. These willow species perform the raw material function in the most effective way and, along with this, absorb carbon dioxide from the atmosphere in the greatest amount.

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