Carbon deposition by oak forests and willow communities

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Abstract. The peculiarities of carbon deposition in stands of oak quiver (Quercus robur L.), as well as in communities of shrub and tree life forms (Salix cinerea L., S. triandra L., S. viminalis L., S. purpurea L., S. fragilis L., S. alba L.). In the oak groves, the largest deposition of carbon is recorded in the fresh pine forest of Shipov, a forest of a late-blossoming species of oak tree, of natural origin at the age of 181 - 386.3 tons·ha⁻¹. In forest oak cultures, the total mass of carbon concentrated in the tree stage has increased from 15.28 to 121.70 tons·ha⁻¹ over the period from 19 to 76 years. High biological productivity of willow communities promotes effective performance of carbon-depositing function. The maximum amount of deposited carbon (31.7 tons·ha⁻¹ for a 5-year life span) is noted in the communities of S. viminalis of sprouts originating in the shrub biomorph. Of all the studied biological species, the maximum phytomass increment is greatest, and accordingly the largest amount of carbon in the growth (5.62 tons·ha⁻¹·year⁻¹) occurs in S. viminalis when it grows in shrubby form.

1. Introduction

Since carbon is necessary to maintain any form of life, any interference in the circulation of this element affects the number and variety of living organisms that can exist on Earth. If current trends continue, the total concentration of CO₂ and other greenhouse gases in the atmosphere will be equivalent to doubling the CO₂ content possibly by 2030, which may lead to an increase in global mean temperatures in a larger amount than has ever happened in human history. As a result of doubling the concentration of CO₂, an average temperature increase of about 1.5-4.5 °C is possible, and the warming should be more significant in the high latitudes of the northern hemisphere in winter than in the equator [1-3]. In this regard, the monitoring of carbon deposition in forest ecosystems as one of the most significant sites of its long-term conservation is of global importance.

Forests of the central black-earth region of the European part of Russia, growing in the steppe and forest-steppe regions, perform extremely important ecological functions: gas regulation, climate regulation, water protection, soil protection, meliorative, biotagging, etc. The purpose of our studies is to assess the impact of hardwood species on deposition of carbon. In this paper, the features of carbon deposition in the stands of Quercus robur L., grown in mountain and bayra conditions, artificial and natural, early and late phenological species, as well as in communities of shrub and tree life forms (Salix cinerea L., S. triandra L., S. viminalis L., S. purpurea L., S. fragilis L., S. alba L.). In Quercus
robur there are two phenological forms: early - leaves bloom in the third decade of April; late - the leaves bloom in early May.

Oak is a long-living tree species, characterized by a high degree of intraspecies diversity and polymorphism. Long-term studies have shown that numerous intraspecific taxonomic categories with certain bioecological properties are formed within the natural range of the oak of the petiolate under the influence of various ecological conditions (climatic, edapho-orographic). OCTR oaks are characterized by a large intraspecific diversity. They are located in two climatic zones in the steppe and forest-steppe, they are distinguished by soil ecotypes: subordinate, cretaceous, solonetnic, they are represented by floodplain, bayar and upland ecotypes, phenological varieties early and late blooming, winter-leafed [4-6]. Willow cenoses grow mainly in river floodplains (which is associated with their high demand for moisture), differ in comparison with oak, rapid growth, but much shorter life expectancy [7].

In the literature there is a significant amount of work on the carbon-depleting function of tree species [8-21]. Many works [4, 5, 9, 16, 19, 20, 22-25] are devoted to the study of carbon-assisting functions of oak forests, but the high level of intraspecies polymorphism of this breed was not always taken into account. Studies of the carbon deposition function of stands of willow cenoses are extremely rare [22], but they prove that, in comparison with oak forests, willow cenoses under optimal conditions of their growth perform it more effectively. This fact is natural, since the value of carbon deposition is directly proportional to the annual productivity of phytomass.

The purpose of this study is to estimate carbon deposition by plant communities that differ significantly in growth energy and longevity — oak and willow cenoses.

2. Methods and characteristics of research objects

To estimate the productivity of the stands, originally by conventional methods [26], a stock of stemwood was established. The carbon deposition was estimated by the methods of [12, 27, 28-31], consistent with the carbon sequestration assessment methodology approved by the Intergovernmental Panel on Climate Change. The essence of the methodology is reduced to the recalculation of the timber stock from cubic meters per ton (based on the density of wood) and the calculation (based on the age-dependent conversion coefficients) of the carbon deposition for the following pools: tree level; dead wood (dead and fallen); the lower tiers of the forest; fallen leaves; organic matter of the soil.

Investigations of the oak forests in the Voronezh region were carried out in the Spy Forest in the forest type (TL) fresh Snytyva oak forest (SDS), dry sedge and very dry saline oak forest, in the plantations of the early (E) and late (L) oak. In dry oaken forests of the steppe zone of the Voronezh region, TL is a bayrachnaya shrub oak (DBCT). In the educational and experimental forestry VGLTU of the Voronezh Forestry University, in the Pravoberezhny and Zhivotinovsky District Forestries, in Vorontsovsky, Krasniy, and in the Kalacheevsky Forestry (Table 1).

The study of forest-typological cultures was carried out in conditions of a fresh ovine drift of the Voronezh Forestry University. In the Kursk region, the age range of oak tree cultures was studied in the interval from 19 to 76 years (Table 2).

Researches of cenoses of willow were made in the floodplain of the Don River in the territory of the Voronezh Region (Table 3). Representatives of the genus Salix in the area of research are represented by plants of shrubby, dendritic and mixed biomorphs. The greatest energy of growth is found in mixed biomorphs under optimal conditions when growing in the form of shrubs.

All objects of research are located in Russia (Voronezh and Kursk regions). Geographical coordinates. Spy Forest 50.67° north latitude, 40.34° east longitude. Forestry of the Voronezh Forestry University 51.72° north latitude, 39.21° east longitude. Kalacheevsky Forestry - 50.41° north latitude, 40.94° east longitude. Forestry typological oak cultures in the Kursk region are 51.53° north latitude, 36.51° east longitude. Willow cenosis in the floodplain of the Don River 51.41° north latitude, 39.02° east longitude.
3. Results and discussion

In the oak forests of the Voronezh region, the largest deposition of carbon (Table 4) is recorded in the fresh pine forest of Shipov, the forest of a late-blossoming species of oak tree, of natural origin at the age of 181 - 386.3 tons·ha⁻¹, which is 88.9 tons·ha⁻¹ (23%) more than, in the plantation of the early-breaking variety of oak tree. In the dry snytevo-sedge oak grove of carbon-bearing origin, the largest carbon deposition is recorded in the plantation with the participation of the early-breaking varieties of oak stems of 316.7 C t / ha, which is 37.0 tons·ha⁻¹ (23%) larger than in the plantation of a late-opening species of oak leaf. In conditions of very dry oak forests on salt soils, the difference in deposition of carbon in plantations with the participation of a late-blossoming and early-opening species of oak leaves is insignificant and amounts to only 2 tons·ha⁻¹ (0.9%). In the Voronezh upland oak grove, natural copulation, TFC - C₃, the largest carbon deposition is recorded in the plantation with the participation of the early-opening species of oak, 298.7 tons·ha⁻¹, which is 52.8 tons·ha⁻¹ (18%) more than in the late spreading plantation varieties of oak tree.

Table 1. Taxation characteristics of the oak groves of the Voronezh Region.

| Composition  | TFC  | Age, years | Medium: height, meters | diameter, centimeters | Stock, m³·ha⁻¹ | Average increase in stock, m³·ha⁻¹·year⁻¹ |
|--------------|------|------------|------------------------|-----------------------|--------------|------------------------------------------|
| Upland oak grove Thorns forest, natural seed | 9QRS 1FR (L) | D₂ 181 | 35 | 60 | 604 | 3.34 |
| Upland oak grove Thorns forest, natural shoots | 8QRS 2FR (E) | D₂ 181 | 32 | 52 | 497 | 2.75 |
| Upland oak forest of Thorns forest, a natural coppice, alkaline soils | 9QRc1 FR (L) | D₁ 86 | 22 | 27 | 315 | 3.66 |
| Upland oak forest of Thorns forest, a natural coppice, alkaline soils | 6QRc3 FR (E) | D₁ 86 | 26 | 30 | 367 | 4.27 |
| Voronezh upland oak grove, natural shoots | 10QRc (L) | D₀ 91 | 17 | 28 | 232 | 2.55 |
| Voronezh upland oak grove, natural shoots | 10QRc (E) | D₀ 91 | 17 | 28 | 229 | 2.52 |
| Voronezh upland oak grove, forest cultures | 10QRS +Til (L) | D₂ 64 | 23 | 24 | 241 | 3.77 |
| Voronezh riparian oak forest, a natural coppice | 7QRS2Til 1Ap (E) | D₂ 64 | 22 | 22 | 155 | 2.42 |
| Voronezh riparian oak forest, a natural coppice | 4QRc5Fr1Pt (E) | D₃ 85 | 25 | 34 | 304 | 3.58 |
| Voronezh-Kalacheevskiy bairachny Dubrava, a natural coppice | 10QRc (L) | E₁ 50 | 21 | 19 | 243 | 4.86 |
| Voronezh-Kalacheevskiy bairachny Dubrava, a natural coppice | 8QRc1Pt1Til (E) | E₁ 50 | 15 | 21 | 145 | 2.90 |
| Voronezh-Kalacheevskiy bairachny Dubrava, a natural coppice | 10QRc (L) | E₂ 50 | 21 | 22 | 201 | 4.02 |
| Voronezh-Kalacheevskiy bairachny Dubrava, a natural coppice | 8QRc2Fr (E) | E₂ 50 | 18 | 18 | 247 | 4.94 |

Notes: TFC - type of forest conditions; Qrc - Quercus robur; Fr - Fraxinus excelsior; Til - Tilia cordata; Ap - Acer platanoides; Pt - Populus tremula; (L) a late-blooming variety; (E) - early-blooming variety. C - type of forest conditions on relatively rich soil; D - type of forest conditions on rich soil; E - type of forest conditions is rich on rich soil.
Table 2. Taxation characteristics of oak crops in the Kursk region.

| Composition stand | TFC | Age, years | Medium: |
|-------------------|-----|------------|---------|
|                   |     |            | height, meters | diameter, centimeters | Stock, m³·ha⁻¹ | Average increase in stock, m³·ha⁻¹·year⁻¹ |
| 10 Qrc            | E₂  | 19         | 6.5      | 5.3      | 39         | 2.05       |
| 10 Qrc            | E₂  | 26         | 8.6      | 8.7      | 82         | 3.15       |
| 10 Qrc            | E₂  | 37         | 10.9     | 10.9     | 129        | 3.49       |
| 10 Qrc            | E₂  | 43         | 12.8     | 15.5     | 157        | 3.65       |
| 10 Qrc            | E₂  | 55         | 15.4     | 17.2     | 211        | 3.84       |
| 10 Qrc            | E₂  | 76         | 21.0     | 25.1     | 303        | 3.99       |

Table 3. Taxation characteristics communities of willow in the floodplain of the Don river.

| The species and life form of the community edifier | TFC | Age, years | Medium: |
|--------------------------------------------------|-----|------------|---------|
|                                                  |     |            | height, meters | diameter, centimeters | Stock, m³·ha⁻¹ | Average increase in stock, m³·ha⁻¹·year⁻¹ |
| Willow shrub biomorph                            |     |            |             |                      |             |                                           |
| *Salix cinerea* (S)                              | D₅f | 8          | 5.0        | 4.1                  | 69.7        | 8.71          |
| Willow mixed biomorph in shrub form              |     |            |             |                      |             |                                           |
| *Salix triandra* (S)                             | C₄f | 5          | 4.1        | 3.1                  | 75          | 15.00         |
| *Salix viminalis* (S)                            | D₄f | 5          | 4.4        | 3.1                  | 99          | 19.80         |
| *Salix purpurea* (S)                             | B₂f | 5          | 4.7        | 3.2                  | 65          | 13.00         |
| Willow mixed biomorphs in tree form              |     |            |             |                      |             |                                           |
| *Salix viminalis* (T)                            | D₃f | 15         | 6.7        | 6.9                  | 105         | 7.00          |
| *Salix purpurea* (T)                             | B₂f | 15         | 6.2        | 5.8                  | 46          | 3.07          |
| Willows of tree-like biomorphs                   |     |            |             |                      |             |                                           |
| *Salix fragilis* (T)                             | D₂f | 30         | 17         | 18                   | 108         | 3.60          |
| *Salix alba* (T)                                 | D₃f | 30         | 14         | 24                   | 136         | 4.53          |

Notes. (S) - shrub life form; (T) - is a tree-like life form. D₅f - marshy growing conditions in the floodplain on rich soil; C₄f - wet growing conditions in the floodplain on relatively rich soil; D₄f - wet growing conditions in the floodplain on rich soil; B₂f - growing conditions in the floodplain on relatively poor soil; D₃f - wet growing conditions in the floodplain on rich soil; D₂f - fresh growing conditions in the floodplain on rich soil.

64 summer forest cultures of English oak created in the right-Bank forest WALL UGLTU largest carbon deposition is noted in the spreading involving posterizeimage varieties of oak 185.1 tons·ha⁻¹, which is 47.4 tons·ha⁻¹ (27%) more than in the imposition renovapurchase varieties of oak. In natural floodplain oak coppice of the Voronezh river, at the age of 85 years, the stock of carbon was 247.0 tons·ha⁻¹. In dry bairachniy Kalacheevskiy Dubrava largest carbon deposition is noted in the spreading involving posterizeimage varieties of oak 226.9 tons·ha⁻¹ representing a 70.7 tons·ha⁻¹ (31%) more than in the imposition renovapurchase varieties of oak. Fresh bairachniy Dubrava difference in the deposition of carbon in plantations with the participation of posterizeimage and renovapurchase varieties of oak-trees is insignificant, amounting to only 8.4 tons·ha⁻¹ (4 %).
In forest oak cultures in the Kursk region, the most active increase in stemwood stock (see Table 2) is recorded before the 26-year-old age of the stand. This circumstance is reflected in the dynamics of the mass of the wood layer. In all the considered age range, the majority of the live weight of the tree layer is in tree trunks (about 66%), a significant proportion is the mass of the root system and branches (13 and 14%), the proportion of leaf mass is relatively low (7%). The proportion of dry land in the total mass of stands is small (no more than 4%).

The maximum amount of carbon (Table 5) is concentrated in the phytomass of the stand; the fraction of carbon deposited in the dead (tree detritus) is from 0 to 4%. The total mass of carbon concentrated in the tree stage during the period from 19 years to 76 years of age increases from 15.28 to 121.70 tons·ha\(^{-1}\), which in this time interval averages 1.86 tons·ha\(^{-1}\) per year.

The high biological productivity of willow communities contributes to the effective implementation of carbon storage function because its value is directly proportional to the phytomass. On the carbon-depleting function affects the species belonging to plants. Willow mixed biomorphs differ from tree and shrub.

| Composition/ Variety | Carbon, tons·ha\(^{-1}\) |
|----------------------|-------------------------|
|                      | Dre. in standing up | Pozemac pitomac with Bedding | Soils (0-30 cm) | Undergrowth | Near juice | Subtotal |
| Upland oak grove Thorns forest, natural seed, D\(_2\), 181 year |
| 9 Qrs 1Fr (L)       | 236.9                | 92.75                | 4.7             | 47.2         | 2.4        | 2.4        | 386.3    |
| 8 Qrs 2 Fr (E)      | 173.9                | 68.2                 | 4.7             | 47.2         | 1.7        | 1.7        | 297.4    |
| Upland oak grove Thorns forest, natural shoots, D\(_1\), 86 years |
| 9Qrc1 Fr (L)        | 151.8                | 73.0                 | 4.7             | 47.2         | 1.5        | 1.5        | 279.7    |
| 6Qrc3 Fr (E)        | 176.4                | 84.8                 | 4.7             | 47.2         | 1.8        | 1.8        | 316.7    |
| Upland oak forest of Thorns forest, a natural coppice, alkaline soils D\(_0\), 91 year |
| 10Qrc (L)           | 111.6                | 53.6                 | 4.7             | 47.2         | 1.1        | 1.1        | 219.3    |
| 10 Qrc (E)          | 110.2                | 53.0                 | 4.7             | 47.2         | 1.1        | 1.1        | 217.3    |
| Voronezh upland oak grove, natural shoots, C\(_2\), 85 years |
| 10 Qrc (L)          | 129.4                | 62.2                 | 4.7             | 47.2         | 1.2        | 1.2        | 245.9    |
| 10 Qrc (E)          | 164.6                | 79.0                 | 4.7             | 47.2         | 1.6        | 1.6        | 298.7    |
| Voronezh upland oak grove, forest cultures, D\(_2\), 64 years |
| 10 Qrs +Til(L)      | 94.5                 | 36.9                 | 4.7             | 47.2         | 0.9        | 0.9        | 185.1    |
| 7Qrc2Til 1Ap (E)    | 60.9                 | 23.7                 | 4.7             | 47.2         | 0.6        | 0.6        | 137.7    |
| Voronezh riparian oak forest, a natural coppice, D\(_3\)P, 85 years |
| 4 Qrc 5Fr1Pt (E)    | 130.3                | 62.5                 | 4.7             | 47.2         | 1.3        | 1.3        | 247.0    |
| Voronezh-Kalacheevskiy bairachny Dubrava, a natural coppice, E\(_1\), 50 years |
| 10 Qrc (L)          | 116.6                | 56.0                 | 4.7             | 47.2         | 1.2        | 1.2        | 226.9    |
| 8 Qrc 1Pt1Til (E)   | 69.5                 | 33.4                 | 4.7             | 47.2         | 0.7        | 0.7        | 156.2    |
| Voronezh-Kalacheevskiy bairachny Dubrava, a natural coppice, E\(_2\), 50 years |
| 10 Qrc (L)          | 96.6                 | 46.3                 | 4.7             | 47.2         | 1.0        | 1.0        | 196.8    |
| 8 Qrc 2Fr (E)       | 102.2                | 49.1                 | 4.7             | 47.2         | 1.0        | 1.0        | 205.2    |
Table 5. Carbon stock in oak cultures of the Kursk region (stand composition 10 Qrc).

| Age, years | Tree stands | Wood detritus | Soil cover | Soils (0-30 cm) | Undergrowth | Underbrus | Total |
|------------|-------------|---------------|------------|----------------|-------------|-----------|-------|
| 19         | 15.28       | 0.55          | 0.07       | 47.2           | 2.19        | 1.37      | 66.66 |
| 26         | 33.43       | 0.27          | 0.01       | 47.2           | 0.32        | 0.25      | 81.48 |
| 37         | 52.80       | 0.27          | 0.00       | 47.2           | 0.00        | 0.18      | 100.45|
| 43         | 62.70       | 1.37          | 0.01       | 47.2           | 0.13        | 0.07      | 111.48|
| 55         | 82.50       | 3.02          | 0.02       | 47.2           | 0.20        | 0.16      | 133.1 |
| 76         | 121.70      | 2.20          | 0.01       | 47.2           | 0.00        | 0.02      | 171.13|

Table 6. Carbon stock in the phytomass of willow cenoses for the period of vital activity, tons·ha⁻¹.

| The species and life form of the community edifier | Age, years | Phytomass components: | Willow shrub biomorph | Willow mixed biomorph in shrub form | Willow mixed biomorphs in tree form | Willow of tree-like biomorphs |
|--------------------------------------------------|------------|------------------------|-----------------------|------------------------------------|-----------------------------------|-----------------------------|
| Salix cinerea (S)                                 | 8          | trunk                  | 14.0                  | 15.1                               | 19.8                              | 21.0                        |
| Salix triandra (S)                                | 5          | roots                  | 2.8                   | 3.0                                | 4.0                               | 4.2                         |
| Salix viminalis (S)                               | 5          | branches               | 5.1                   | 3.2                                | 4.2                               | 4.4                         |
| Salix purpurea (S)                                | 5          | leaves                 | 5.3                   | 2.7                                | 3.6                               | 0.9                         |
| Salix viminalis (T)                               | 15         | trunk                  | 21.0                  | 21.0                               | 21.0                              | 21.0                        |
| Salix purpurea (T)                                | 15         | roots                  | 4.2                   | 4.2                                | 4.2                               | 4.2                         |
| Salix fragilis (T)                                | 15         | branches               | 4.4                   | 4.4                                | 4.4                               | 4.4                         |
| Salix alba (T)                                    | 15         | leaves                 | 0.9                   | 0.9                                | 0.9                               | 0.9                         |

Notes. (S) – (S) - shrub life form; (T) is a tree-like life form.

As can be seen from Tables 4-6, both in oak forests and willow cenoses, irrespective of their origin, the maximum proportion of carbon is concentrated in the long-term storage depot (phytomass of the stand, undergrowth, undergrowth without taking into account leaves and live soil cover) and no more than 20% - in the depot of one-year storage (living soil cover, as well as the leaf mass of the stand, undergrowth, undergrowth). Of all the depots of carbon, the main importance is the phytomass of the tree layer. In this case, the sheet mass is not taken into account, since in a short period of time the carbon concentrated in it passes into the soil. Taking into account the above, it is possible to compare the cenoses of different species composition by the amount of carbon deferred in the wood layer. When comparing communities of different ages, the objective indicator is the amount of carbon deferred in the annual increment of the phytomass of the tree layer.

At an early age, willow communities significantly exceed oak forests with respect to growth energy, in this connection, in the 19-year-old oak cultures, the minimum carbon stock in the annual increment of wood is also noted (Figure 1). The Salix fragilis stands at the age of 30 and the 15-year-old Salix purpurea stands in an annual increment have deposited approximately equal amounts of carbon (0.85 and 0.86 tons·ha⁻¹·year⁻¹, respectively). In oak groves of natural origin, the maximum amount of carbon in a year-old increment (2.05 tons·ha⁻¹·year⁻¹) was noted at the age of 86 at
vegetative origin. Throughout the considered time interval of the researched oak cultures an increase in the amount of carbon in the annual increment of wood was noted. Of all the studied biological species, the maximum phytomass increment is greatest, and accordingly the largest amount of carbon in the growth (5.62 tons·ha\(^{-1}\)·year\(^{-1}\)) occurs in *Salix viminalis* when it grows in shrubby form. All shrubbery willows accumulated carbon in a year's increment of more carbon than all oak forests.

![Figure 1. Annual carbon deposition in 1 hectare of communities depending on the species composition. Notes. (S) – (S) - shrub life form; (T) is a tree-like life form.](image)

Based on the studies carried out, the following conclusions and recommendations for production can be made. Carbon deposition in oak forests occurs at different rates and depends on their origin (natural or forest cultures), forest conditions, the age of the stand, the phenological species of the oak tree. To increase the carbon-assisting functions of oak forests, it is necessary to organize forest management, taking into account the silvicultural and ecological features of ecotypes and phenological varieties of the oak tree. The plantations of oak seedling of natural origin are the most productive stable and durable.
4. Summary

It is recommended to harvest acorns taking into account the phenological variety of oak. To measures aimed at increasing the carbon-assisting functions of the oak forests of the region, one should include: promoting natural renewal; the creation of forest cultures taking into account the ecological features of ecotypes and phenological varieties of oak tree; timely removal of dead trees by selective sanitary felling in mature stands and felling in young growth, middle-aged and growing stands, pest and disease control, littering of forests.

In comparison with oak forests, willow communities are less durable, by the age of ripeness they accumulate a much smaller amount of carbon in the phytomass, but when grown in shrubby form, annual accumulation of carbon in them is greater in comparison with oak forests. This does not indicate the expediency of growing instead of oak fast-growing species, in particular willows. Each breed occupies its ecological niche. The task of foresters within these niches is to create optimal conditions for the growth of plant-specific types specific for specific conditions. This will solve not only the economic task of growing wood, but will also promote more efficient carbon deposition.

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