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GENESIS AND GEOGRAPHY OF SOILS

Accumulation of Organic Carbon in Chernozems (Mollisols) under Shelterbelts in Russia and the United States

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Abstract—Shelterbelts that were created in place of meadow and meadow-steppe landscapes of the forest-steppe zone of northern continents serve as areas of carbon accumulation and participate in the formation of soil organic matter. In the Great Plains of the United States (in North Dakota, South Dakota, and Nebraska) and on the Central Russian Upland (Belgorod, Voronezh, and Kursk oblasts), a general tendency toward an increase in the C_{org} pool in the topsoil (0–30 cm) from the marginal parts of the shelterbelts toward their central parts by about 3.5–10.0 t per each 10 m has been identified. In 55 years of the existence of shelterbelts on chernozems in the European part of Russia, the mean annual rate of the organic carbon accumulation in the upper meter has been varying within 0.7–1.5 t/ha. In 19 years of the existence of a shelterbelt in the area of Huron (South Dakota), the mean annual rate of the organic carbon accumulation in the 1-m-thick layer of the Bonilla soil series (Haplustolls) has reached 1.9 t/ha.

Keywords: agroforest reclamation, climate change, northern continents, forest steppe, soil organic carbon

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INTRODUCTION

The study of the anthropogenic transformation of soils is one of the pressing challenges of modern pedology. The complexity of this problem and the need to compare data obtained in different regions for its adequate solution foster the development of cooperation between scientists; such studies are often performed by international teams [4, 25, 27].

In a wide range of problems of the anthropogenic transformation of soils under the impact of various technogenic factors (technopedogenesis), the problems of soil transformation under the impact of agroforest reclamation can be separately distinguished. Many aspects concerning the influence of shelterbelts on the properties of soils have been studied sufficiently well [3, 10, 14, 24, 26]. At the same time, many problems have yet to be studied. In particular, this concerns the influence of shelterbelts on the production and accumulation of soil organic matter [7, 8, 11, 12, 30, 31].

It is known that the scientific study of the role of shelterbelts for steppe soils and of the possibilities to afforest steppe landscapes was initiated by V.V. Dokuchaev during his expedition in 1891. The scientific basics of the transformation of steppe landscapes into agroforest cultural landscapes were shaped in the works of Dokuchaev; he demonstrated the ameliorative role of trees and shrubs in the steppe zone [11]. In the 20th century, Russian experience in agroforest reclamation became widely accepted as a method of protection of soils from water and wind erosion. In particular, it was introduced in the east of the Great Plains of the United States after catastrophic dust storms in the 1930s [29, 33].

A favorable influence of shelterbelts on the soils and environment is generally recognized. Shelterbelts not only reduce the risk of soil erosion but also produce a number of other positive effects, including (a) the improvement of the microclimate owing to snow retention in the winter, lower evaporation in the summer, and the accumulation of available water in the spring and summer; (b) the increase in the yield of crops; (c) the formation of specific habitats for wildlife; and (d) the betterment of the aesthetic perception of the landscape [1, 9, 23, 24, 26, 28].

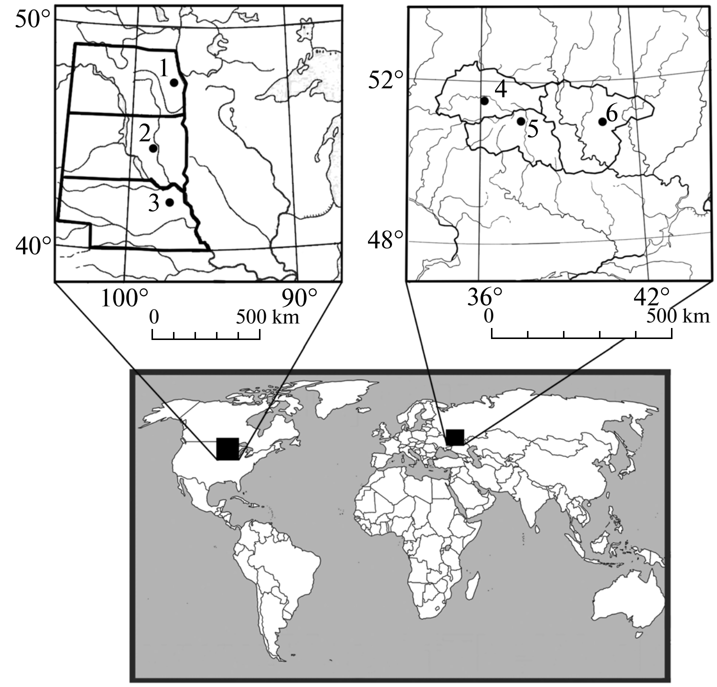

Fig. 1. Location of the studied key sites: (1) Reynolds (North Dakota), (2) Huron (South Dakota), (3) Norfolk (Nebraska), (4) Streletskaya Steppe (Kursk oblast), (5) Yamskaya Steppe (Belgorod oblast), and (6) Kamennaya Steppe (Voronezh oblast).

In light of the problem of global climate change, the study of shelterbelt ecosystems involves new aspects. These ecosystems can be considered carbon sinks owing to the organic carbon sequestration in the phytomass and in the soil organic matter. There are many works devoted to these problems. However, there is a need for more complete regional data and better justified methodological approaches to such studies.

In this context, the aim of our paper is to identify and analyze changes in the organic carbon content of the soils of meadow-steppe and meadow landscapes of the northern continents with the widespread development of arable farming and the creation of shelterbelts.

OBJECTS AND METHODS

We studied meadow-steppe chernozems of the forest-steppe zone on the Central Russian Upland and prairie soils in the western part of the corn belt of the United States in the northeast of the Great Plains. These soils were studied under different types of vegetation, including virgin communities, croplands, and shelterbelts.

The location of the key sites of our study is shown in Fig. 1.

In the selection of these key sites, we were guided by the following requirements: (a) the key sites should be found in the forest-steppe zone of the northern continents; (b) they should be located on flat interfluve surfaces; and (c) the particular plots under different types of vegetation (virgin, cropland, and shelterbelt in place of the former cropland or former steppe) should be located close to one another, within the area of a given soil developed from the same parent material.

Such key sites in Russia were selected near the reserved and specially protected meadow-steppe landscapes of the forest-steppe zone, i.e., near the Alekhin Central Chernozemic Reserve (the Streletskaya Steppe area, Kursk oblast, 51°32′ N, 36°05′ E), near and within the Belogor'e Reserve (the Yamskaya Steppe area, Belgorod oblast, 51°11′ N, 37°37′ E), and in the Kamennaya Steppe (the Kamennaya Steppe area, Voronezh oblast, 51°02′ N, 40°44′ E). In the United States, the Reynolds key site in North Dakota (47°42′ N, 97°11′ W), the Huron key site in South Dakota (44°16′ N, 98°15′ W), and the Norfolk key site in Nebraska (42°03′ N, 97°22′ W) were selected (the names are given according to the names of the nearby cities).

We tried to select the key sites on well-drained watershed areas. In some cases, this was a difficult challenge because of the widespread recent development of secondary hydromorphism of chernozems and the corresponding soil degradation processes in European Russia [5]. Thus, as shown by Khitrov and Cheverdin [18], the number of areas with seasonally waterlogged soils has increased in the Kamennaya Steppe area. In relation to this, we had to consult with soil scientists having detailed information on the soil cover patterns in the investigated areas.

Table 1. Some physiographic characteristics of the key sites

Orographic region	Name of key site	Absolute height, m a.s.l.	Parent material	Soils	Annual precipitation, mm	Mean annual temperature, °C	Hydrothermic coefficient
Central Russian Upland, Russia	Streletskaya Steppe	240	1	Leached chernozems	580	+5.3	1.23
	Yamskaya Steppe	230	1	Typical chernozems	530	+5.6	1.1
	Kamennaya Steppe	190	2	Ordinary chernozems (transitional to typical chernozems)	480	+5.8	1.0
Great Plains, USA	Norfolk	470	3	Haplustolls of the Thurman series (leached chernozems)	700	+9.6	1.47
	Reynolds	430	4	Argiaquolls of the Mustinka series (meadow-chernozemic soils)	530	+4.4	1.41
	Huron	440	5	Haplustolls of the Bonilla series (chernozemic meadow soils)	580	+7.7	1.31

Parent materials: (1) loess-like calcareous loam, (2) loess-like calcareous clay, (3) light loam over glaciofluvial loamy sand, (4) thin calcareous loam over glaciofluvial gravelly sandy deposits, and (5) glaciolacustrine calcareous gravelly loam.

In the United States, the Norfolk key site is found on a well-drained interfluve. As for the Reynolds and Huron key sites, they are located on relatively poorly drained territories with a shallow groundwater table.

Data on the absolute heights of the key sites, their climatic parameters, parent materials, and classification position of the studied soils are summarized in Table 1.

Traditional technologies of crop growing are applied on the key sites.

In the United States, the studied plowed lands of agroforest landscapes are managed by farmers. The age of their agricultural use is estimated at 120 years for the Norfolk site, 110 years for the Reynolds site, and 21 year for the Huron site. The following crops are grown in rotation: wheat, corn, soybeans, and sunflowers on the Reynolds site; corn, soybeans, and sorghum on the Huron site; and corn, soybeans, wheat, and lucerne on the Norfolk site.

Despite the measures aimed at improving the fertility of cultivated soils (mainly, the application of mineral fertilizers by farmers), the problem of the depletion of soil humus reserves is typical of all the studied plowed soils of the Great Plains.

Plowed lands of the key sites in Russia belong to large agricultural enterprises (Yamskaya Steppe and Kamennaya Steppe), or to individual farmers (Streletskaya Steppe). The age of their agricultural use is estimated at about 150 years. Cereals and row crops are grown in rotation. Under somewhat colder and wetter conditions of the forest steppe (the Yamskaya Steppe and Yamskaya Steppe key sites), the portion of fodder beet and sugar beet in the rotation is somewhat higher than that under somewhat drier conditions of the Kamennaya Steppe, where the portion of cereals and sunflower in the rotation is increased. In general, the agrotechnology used in these areas is typical of the southern part of central Russia. Until recently, extensive farming predominated. Under these conditions, the amount of applied organic fertilizers could not compensate for the dehumification processes in the cultivated chernozems.

The shelterbelts created on the selected key sites in Russia and in the United States consist of multiple tree rows ensuring their “windproof” properties. The width of the studied shelterbelts varies from 20 to 35 m. The shelterbelts in Russia were planted in the 1950s; their age is about 55 years. These shelterbelts were planted on former plowland with the age of about 95 years (at the moment of the planting of the trees). The shelterbelts consist of the following tree species: black poplar (*Populus nigra*) and silver birch (*Betula verrucosa*) at the Streletskaya Steppe key site, American maple (*Acer negundo*) at the Yamskaya Steppe key site, and English oak (*Quercus robur*) and balsam poplar (*Populus balsamifera*) at the Kamennaya Steppe key site. Artificially planted shelterbelts examined in the United States have different ages: 70 years (Norfolk key site), 53 years (Reynolds key site), and 19 years (Huron key site). At the Norfolk and Reynolds key sites, the shelterbelts were planted in place of former croplands of 50 and 57 years in age, respectively. At the Huron key site, the artificial forest plantation is not a shelterbelt proper. It represents a multirow plantation of trees occupying a rectangular land plot of several hectares in area. In the south, it borders the cropland; in the west, it borders the virgin land plot. Earlier, similar virgin vegetation existed all over the studied key site. The trees at the Huron key site were planted on 2-year-old cropland (after plowing

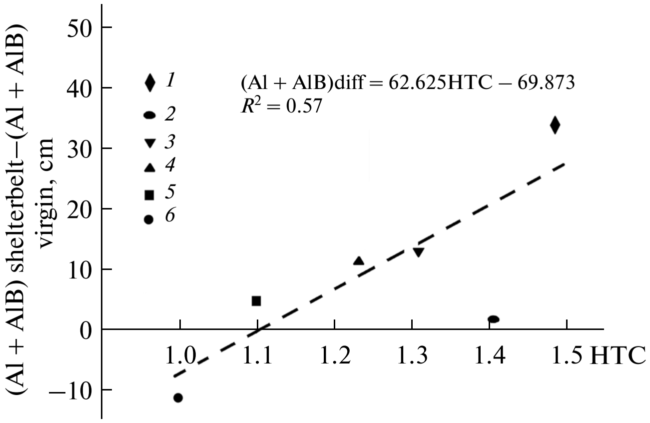

Fig. 2. Changes in the thickness of the humus profile of soils under the shelterbelts (as compared with the soils of virgin plots) versus the values of the hydrothermic coefficient (HTC) calculated for the key sites: (*1*) Norfolk (Nebraska), (*2*) Reynolds (North Dakota), (*3*) Huron (South Dakota), (*4*) Streletskaya Steppe (Kursk oblast), (*5*) Yamskaya Steppe (Belgorod oblast), and (*6*) Kamennaya Steppe (Voronezh oblast).

the virgin land). We suppose that no considerable loss of soil organic matter could have taken place in such a short period of time. Therefore, we can estimate the changes in the soil humus status under the forest plantation via comparing it with that of the virgin soil.

The Norfolk shelterbelt is composed of cottonwood poplar (*Populus deltoides*), Siberian elm (*Ulmus pumila*), and red mulberry (*Morus rubra*); the Reynolds shelterbelt contains green ash *Fraxinus pennsylvanica* and red cedar (*Juniperus virginiana*). The Huron forest plantation consists of green ash, red cedar, and oak (*Quercus macrocarpa*).

The identification of the key sites included the analysis of the maps compiled in different years and remote sensing materials; consultations with specialists in geography, geobotany, and agroforest reclamation; and reconnaissance visits to the proposed territory. It was important to prove the initial natural homogeneity of the soils within the examined key sites. For this purpose, large-scale (1 : 10000 in Russia and 1 : 20000 in the United States) soil maps were analyzed. The soils under different types of vegetation had to belong to the same soil series (in the United States) or to the same soil genus (in Russia) in agreement with the corresponding soil classification systems. Then, this information was verified in the field during reconnaissance surveys. Strictly speaking, an unambiguous identification of the soil cover homogeneity can only be achieved in the course of detailed soil surveys or in the study of long soil trenches. In particular, this was shown during special soil surveys in the Kamennaya Steppe [15, 17, 19]. At the same time, a comparative analysis of soil formation under the croplands and shelterbelts included careful examination of corresponding soil profiles, during which we could judge the degree of their initial similarity [7, 8, 12].

The soils of the studied key sites are somewhat different and should be analyzed separately (they cannot be included in one statistical sample). However, the fact that we found similar tendencies of changes in the soil properties (in the thickness of humus profiles and in the content and total storage of organic carbon) under the shelterbelts in comparison with the adjacent cropland at all the key sites made it possible to suppose that the shelterbelts exert quite definite influence on the soil humus profiles.

The field studies of the key sites were performed using the same approach. We sampled the topsoil (0–30 cm) along three parallel lines crossing the shelterbelts and spaced 5 m apart from one another; the sampling points on these lines were spaced 4–5 m apart from one another. At each point, three soil samples were taken and then mixed to obtain the average sample. Overall, the sampling was performed at 18 points along each of the lines, including 6 points under the shelterbelts and 4 points under the adjacent land plots on each side of the shelterbelts. The width of the shelterbelts differed from 20 to 35 m. Thus, overall, the area sampled under each shelterbelt varied within 200–350 m^2 and had the width of 10 m (the three sampling lines). The areas sampled on both sides of the shelterbelts varied within 120–150 m^2. This method of soil sampling with the following statistical treatment of the results is widely practiced for studying agroforest landscapes in the United States [30, 32].

Additionally, we examined the soil profiles in large soil pits (3 × 1 m) and in several boreholes. The soil pits were dug in the central parts of the shelterbelts and on each of the adjacent plots at maximum distances from the shelterbelts (within the sampling zone). The distances between the soil pits under the shelterbelts and under the plowlands were about 25–35 m.

The soils of virgin plots were studied in large soil pits and in deep boreholes.

In essence, our approach was based on the comparative analysis of the soil profiles and soil characteristics under the shelterbelts and on the adjacent plots. This is a common approach in modern soil science [7, 12].

The soil samples were taken to study the organic carbon content and determine the soil bulk density; cutting rings (in the soil pits) and special soil augers of known volume were used to take the samples.

The organic carbon (C_{org}) content was determined by the dry combustion method (Fison NA 15000 Elemental Analyzer, ThermoQuest Corp., Austin, TX) at the National Laboratory for Agriculture and the Environment (USDA) in Ames, Iowa.

RESULTS AND DISCUSSION

An important morphogenetic characteristic of the direction of soil changes in the virgin plot–plowland–shelterbelt sequence is the thickness of the soil humus profiles, i.e., the total thickness of the A1 (Ap + A1) and A1B horizons (Table 2).

Table 2. Statistical parameters of the thickness (cm) of humus horizons and humus profiles at the key sites

Land use	Horizon	*n*	Lim	$X \pm \delta_X$	δ	V, %
Reynolds, North Dakota						
Virgin plot	A1	15	40–46	42.8 ± 0.5	1.97	4.6
	A1 + A1B	15	46–55	51.9 ± 0.8	2.95	5.7
Shelterbelt	A1	15	32–42	37.9 ± 0.6	2.43	6.4
	A1 + A1B	15	51–58	53.6 ± 0.5	2.03	3.8
Plowland	Ap + A1	15	20–25	22.8 ± 0.3	1.32	5.8
	Ap + A1 + A1B	15	20–25	22.8 ± 0.3	1.32	5.8
Huron, South Dakota						
Virgin plot	A1	15	40–50	44.3 ± 0.7	2.63	5.9
	A1 + A1B	15	40–50	44.3 ± 0.7	2.63	5.9
Shelterbelt	A1	15	52–60	56.1 ± 0.6	2.29	4.1
	A1 + A1B	15	52–60	56.1 ± 0.6	2.29	4.1
Plowland	Ap + A1	15	29–34	31.3 ± 0.4	1.50	4.8
	Ap + A1 + A1B	15	37–48	40.6 ± 0.8	3.00	7.4
Norfolk, Nebraska						
Virgin plot	A1	15	18–30	24.9 ± 0.7	2.83	11.4
	A1 + A1B	15	37–47	40.9 ± 0.8	3.00	7.3
Shelterbelt	A1	15	37–47	42.1 ± 0.8	3.25	7.7
	A1 + A1B	15	64–80	74.8 ± 1.3	4.87	6.5
Plowland	Ap + A1	30	35–49	42.3 ± 0.7	4.00	9.5
	Ap + A1 + A1B	30	60–69	63.6 ± 0.5	2.75	4.3
Streletskaya Steppe, Kursk oblast						
Virgin plot	A1	15	40–54	44.7 ± 0.9	3.30	7.4
	A1 + A1B	15	60–77	70.3 ± 1.0	3.87	5.5
Shelterbelt	A1	15	35–50	44.6 ± 1.3	5.19	11.6
	A1 + A1B	15	75–85	81.4 ± 1.0	3.80	4.7
Plowland	Ap + A1	30	33–48	37.3 ± 0.6	3.48	9.3
	Ap + A1 + A1B	30	47–80	63.1 ± 2.0	10.83	17.2
Yamskaya Steppe, Belgorod oblast						
Virgin plot	A1	15	47–58	52.9 ± 0.9	3.45	6.5
	A1 + A1B	15	69–80	75.5 ± 0.9	3.36	4.5
Shelterbelt	A1	15	46–64	60.1 ± 1.9	7.31	12.2
	A1 + A1B	15	71–92	80.1 ± 1.6	6.29	7.9
Plowland	Ap + A1	30	39–56	45.3 ± 0.9	4.65	10.3
	Ap + A1 + A1B	30	54–82	69.2 ± 1.3	6.87	9.9
Kamennaya Steppe, Voronezh oblast						
Virgin plot	A1	15	41–55	44.7 ± 0.9	3.56	8.0
	A1 + A1B	15	69–88	75.5 ± 1.3	4.91	6.5
Shelterbelt	A1	15	46–55	49.6 ± 0.8	3.09	6.2
	A1 + A1B	15	57–70	64.1 ± 1.0	3.80	5.9
Plowland	Ap + A1	30	37–47	41.0 ± 0.4	2.37	5.8
	Ap + A1 + A1B	30	49–64	58.5 ± 0.6	3.52	6.0

Here and in Tables 3 and 4, *n* is the sample size; Lim is the limits of variation; X is the mean arithmetic, δ_X is the error of the mean, and V is the coefficient of variation (%).

Table 3. Statistical parameters of the pools of soil organic carbon (t/ha) in the layer of 0–30 cm at the key sites studied in Russia and in the United States

Land use	n	Lim	$X \pm \delta_X$	δ	V, %
Streletskaya Steppe					
Virgin plot	6	119.9–135.4	126.2 ± 2.3	5.55	4.4
Shelterbelt	18	109.9–241.1	126.4 ± 7.0	29.74	23.5
Plowland	24	91.5–126.7	109.3 ± 2.1	10.24	9.4
Yamskaya Steppe					
Virgin plot	6	131.2–155.9	138.0 ± 3.9	9.44	6.8
Shelterbelt	18	119.3–163.2	142.1 ± 3.0	12.81	9.0
Plowland	24	111.2–156.8	127.2 ± 2.4	11.80	9.3
Kamennaya Steppe					
Virgin plot	6	135.9–170.0	152.5 ± 4.7	11.40	7.5
Shelterbelt	18	104.4–156.5	125.0 ± 3.3	14.10	11.3
Plowland	24	100.0–140.7	123.6 ± 2.2	10.98	8.9
Norfolk					
Virgin plot	3	39.7–53.8	45.7 ± 4.2	7.28	15.9
Shelterbelt	18	29.7–51.2	38.4 ± 1.4	6.00	15.6
Plowland	24	18.0–35.6	23.9 ± 0.8	3.81	15.9
Reynolds					
Virgin plot	12	95.7–110.3	102.7 ± 1.4	4.76	4.6
Shelterbelt	18	99.5–117.2	107.3 ± 1.2	5.21	4.9
Plowland	12	75.5–101.8	93.4 ± 2.2	7.69	8.2
Huron					
Virgin plot	3	44.6–48.4	46.2 ± 1.1	1.96	4.2
Forest plantation	24	51.0–83.3	65.8 ± 1.6	7.90	12.0
Plowland	24	37.2–50.8	43.8 ± 0.7	3.48	7.9

On all the studied plots, the thickness of the humus profiles under the shelterbelts was reliably larger than that under the adjacent plowed fields; on the average, the difference was about 15 cm. In four cases out of the six studied key sites (except for the Kamennaya Steppe and Reynolds key sites), the thickness of the humus profiles under the shelterbelts was also reliably larger (by 16 cm) than that in the soils of virgin plots.

These differences can be attributed to the processes of soil decompaction under the shelterbelts owing to the loosening action of the roots of the trees and higher activity of burrowing animals (mainly, earthworms) in comparison with the soils of virgin plots. The activation of the humus-accumulative process under conditions of a cooler microclimate of the shelterbelts (in comparison with the virgin plots and plowlands) is also possible. A specific feature of the soils at the Reynolds key site is the presence of a layer of gravelly moraine in the lower part of the humus layer (at the depth of 38–56 cm in the virgin soils). This layer could hamper the downward development of the humus-accumulative part of the soil profile under the shelterbelt at this key site.

The dependence between the observed changes in the thickness of the soil humus layer under the shelterbelts (in comparison with the virgin soils) and the hydrothermic coefficient values calculated for the forest-steppe areas of central Russia and for the Great Plains is shown in Fig. 2.

It has a linear pattern, except for the Reynolds site. As noted above, the presence of the gravelly moraine layer could hamper the development of the humus profile in the soil under the shelterbelt.

An increase in the thickness of the humus-accumulative layer in the soils of the forests-steppe zone under the shelterbelts by 10 cm is accompanied by the increase in the hydrothermic coefficient value by 0.15. In the forest-steppe zone of Eastern Europe, this corresponds to a shift by 50–100 km (75 km on the average) in the northwestern direction.

The revealed linear dependence between the increment in the thickness of the humus-accumulative layer under the shelterbelts and the value of the hydrothermic coefficient has yet to be confirmed by studies on new objects. We suppose that this is an interesting fact that deserves more attention.

The sampling from the topsoil (0–30 cm) on most of the key sites showed that the pools of C_{org} in this layer under the shelterbelts are higher than those in the soils of the adjacent plowlands (Table 3). The difference is statistically significant for most of the plots. For the Streletskaya Steppe, Yamskaya Steppe, Reynolds, and Huron key sites, the pools of C_{org} under the shelterbelts were also higher than or comparable with those in the soils of virgin plots. This confirms the activity of humus-accumulative processes under the shelterbelts.

Note that the changes in the pools of C_{org} and in the soil bulk density under the shelterbelts have quite definite tendencies and generally decrease from the central parts of the shelterbelts toward their margins (Fig. 3, Table 4).

The observed regularities allow us to consider shelterbelts as specific geosystems with their own inner structure. As follows from Fig. 3 and Table 4, optimum conditions for the production and accumulation of the soil organic matter exist in the central parts of the shelterbelts. This may be due to their microclimatic parameters, i.e., cooler and wetter conditions in comparison with those in the peripheral parts of the shelterbelts. At the studied key sites, the gradient of decrease in the pools of C_{org} (in the upper 30 cm) from the central parts of the shelterbelts toward the adjacent plowlands varies from 3.5 t/ha (Kamennaya Steppe) to 10 t/ha (Streletskaya Steppe) per each 10 m with the average value of 7.3 t/ha per 10 m.

The distribution of C_{org} pools in the soil profiles has the following patterns. In the virgin soils, the layer of 0–50 cm contains 74% of the total pool of C_{org} in the 1-m-deep soil layer (Table 5).

In the soils under the shelterbelts, an increase in the C_{org} pool in the layer of 50–100 cm takes place. The upper 50 cm contains 68% (on average) of the total C_{org} pool in the 1-m-deep soil layer (Table 5). This layer contains about 70% of the total pool of C_{org} in the 1-m-deep layer in plowlands next to the shelterbelts. In this case, the decrease in the role of the topsoil in the total humus storage is due to a more active dehumification in the topsoil rather than due to the additional accumulation of humus in the deep soil layers.

The redistribution of the reserves of organic carbon in the soil profiles under the shelterbelts cannot be explained by the inherited humus from the previous plowed stage of the development of these soils. An increase in the relative reserves of C_{org} in the layer of 50–100 cm is observed under the shelterbelts studied at the Streletskaya Steppe, Yamskaya Steppe, Kamennaya Steppe, and Huron key sites. Moreover, the pools of C_{org} in this layer under the shelterbelts at these sites are even higher than those in the virgin soil profiles (Table 4).

To reconstruct the C_{org} dynamics in the studied soils before the creation of the shelterbelts, we should know the regularities of the C_{org} behavior in the durably cultivated automorphic soils of the studied regions. In the forest-steppe zone of European Russia, such studies have been performed for many years. Their results can be found in [13, 21, 22]. As for the northeast of the Great Plains, the authors do not have this information. Therefore, at present, the suggested reconstruction can only be applied to the objects studied in Russia.

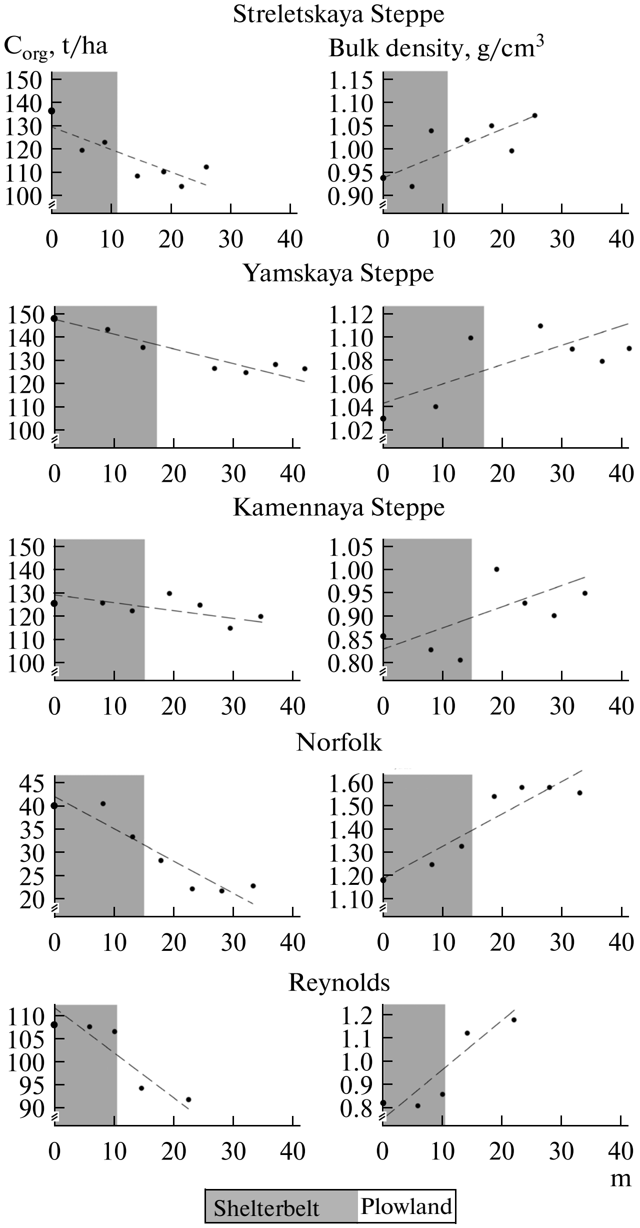

Fig. 3. Spatial trends of changes in the C_{org} pools and in the soil bulk density in the layer of 0–30 cm in the direction from the center of the shelterbelts toward the adjacent plowlands. Each point on the plots gives the average from six samples.

The agrotechnogenic evolution of the C_{org} storage in the chernozems on leveled interfluves was studied by us earlier on three key sites in the forest-steppe zone of the Central Russian Upland. The climatic, lithological, and soil conditions of these key sites are very similar to the key sites of the Streletskaya Steppe, Yamskaya Steppe, and Kamennaya Steppe. The earlier

Table 4. Pools of soil organic carbon (t/ha) under the central and peripheral parts of the shelterbelts and on the adjacent plowlands (15 m apart from the shelterbelts) in the layer of 0–30 cm ($X \pm \sigma_x$; $n = 6$ for each point)

Land use	Streletskaya Steppe	Yamskaya Steppe	Kamennaya Steppe	Norfolk	Reynolds
Center of the shelterbelt	136.7 ± 2.1	147.4 ± 5.1	126.0 ± 7.6	26.7 ± 1.5	108.0 ± 2.5
Margin of the shelterbelt	122.6 ± 2.8	136.1 ± 3.2	122.5 ± 5.5	21.3 ± 1.3	106.7 ± 2.0
Plowland	113.0 ± 3.8	124.5 ± 3.5	121.1 ± 4.9	15.3 ± 0.8	92.2 ± 4.2

Table 5. Pools of soil organic carbon on the virgin plots, under the shelterbelts, and under the adjacent plowlands at the key sites in the United States and Russia (first number in t/ha; second number in % of the total pool in the 1-m-deep soil layer)

Layer, cm	Key site					
	Streletskaya Steppe	Yamskaya Steppe	Kamennaya Steppe	Norfolk	Reynolds	Huron
			Virgin plots			
0–50	175.0/72	208.2/66	227.9/67	61.7/79	182.4/81	66.7/78
50–100	68.5/28	105.7/34	113.6/33	16.5/21	42.5/19	19.2/22
0–100	243.5/100	313.9/100	341.5/100	78.2/100	224.9/100	85.9/100
			Shelterbelts			
0–50	178.6/63	237.3/63	208.6/59	44.9/67	166.0/82	90.8/73
50–100	104.6/37	139.7/37	147.3/41	22.4/33	36.2/18	34.2/27
0–100	283.2/100	377.0/100	355.9/100	67.3/100	202.2/100	125.0/100
			Plowlands			
0–50	188.5/67	186.6/60	189.9/67	35.3/69	108.5/81	65.0/76
50–100	93.8/33	126.2/40	95.3/33	15.9/31	25.0/19	20.3/24
0–100	282.4/100	312.8/100	285.2/100	51.2/100	133.5/100	85.3/100

examined chronosequences of chernozems were found in Ivnyansk (slightly podzolized chernozems), Prokhorovo (typical chernozems), and Gubkin (typical chernozems) districts of Belgorod oblast. For all of them, a unidirectional dehumification of the plow layer (0–30 cm) and the entire soil profiles in the course of the soil plowing was established. It was found that the temporal changes in the pools of humus in the layers of 0–30 and 0–50 cm are described by similar exponential curves (despite considerable distances between the examined plots), whereas the temporal changes in the pools of humus in the layer of 0–100 cm are described by linear trends [22]. On the plots generalizing data on humus loss from the three studied chronosequences of plowed soils relative to the humus pools in virgin chernozems (Fig. 4), arrows and figures indicate humus losses corresponding to 95 years of soil plowing (this is the age of the soil plowing at the Streletskaya, Yamskaya, and Kamennaya Steppe key sites before planting of the shelterbelts), as the total age of the soil plowing is 150 years, and the age of the shelterbelts is 55 years. The values of the relative loss of humus in 95 years of soil cultivation were used to reconstruct the soil humus content at the moment of the creation of the shelterbelts (Table 6).

Our studies indicate that it is incorrect to use data on the organic carbon pools in the soils of plowlands near the shelterbelts to reconstruct the organic carbon pools under the shelterbelts at the time of their planting. The development of dehumification in the plowed soils is slowed under the influence of the shelterbelts. This is seen from the comparison of data on the C_{org} pools in the chernozems plowed for 150 years near the shelterbelts and away from them. The organic carbon content in the soils near the shelterbelts was reliably higher than that at some distance from the shelterbelts. This is explained by the additional input of leaf litter to the soils near the shelterbelts. These soils are also enriched in decaying tree roots. The remains of the root system of trees have been found in soil pits as far as 12–15 m from the margins of the shelterbelts.

In Table 5, the calculated characteristics of the C_{org} budget in the soils under the shelterbelts are given for the key sites studied in Russia. It also contains data on the organic carbon budgets in the soils of the Huron key site in the United States. In this case of a relatively young forest plantation, the initial storage of C_{org} under the plantation was taken equal to that in the virgin soil. It can be concluded from these data that chernozems and Mollisols under artificially planted shelterbelts (or forest plantations) are enriched in organic

Table 6. Pools of soil organic carbon in the soils under the shelterbelts at the time of their planting, t/ha

Layer, cm	Streletskaya Steppe			Yamskaya Steppe			Kamennaya Steppe			Huron		
	1	2	3	1	2	3	1	2	3	1	2	3
0–30	126.4	111.0	+15.4	142.1	121.4	+20.7	125.0	134.2	–9.2	68.3	46.2	+22.1
0–50	191.6	154.0	+37.6	229.3	183.2	+46.1	206.5	200.5	+6.0	88.3	66.7	+21.6
0–100	296.1	224.0	+72.1	369.0	288.8	+80.2	353.8	314.2	+39.6	122.5	85.9	+36.6

(1) Pools of C_{org} in the soils under the shelterbelts, (2) pools of C_{org} in the soils at the time of planting of the shelterbelts (reconstructed from data of Fig. 4 for the Streletskaya Steppe, Yamskaya Steppe, and Kamennaya Steppe), and (3) difference between (1) and (2).

matter. Thus, agroforest reclamation favors the removal of carbon dioxide from the atmosphere with the organic carbon sequestration in the forest phytomass and in the soil organic matter.

According to our calculations, in 55 years of the existence of the shelterbelts, the pools of organic carbon additionally accumulated in the 1-m-deep soil layer have reached 80 t/ha at the Yamskaya Steppe, 72 t/ha at the Streletskaya Steppe, and 40 t/ha at the Kamennaya Steppe key sites. In 19 years of the existence of the forest plantation at the Huron key site, the C_{org} pool in the 1-m-deep soil layer has increased by 37 t/ha (in comparison with that in the former virgin soil in place of the forest plantation) (Table 6). The average rate of organic carbon accumulation in the soil layer of 0–100 cm under the shelterbelts varies from 0.7 t/ha (Kamennaya Steppe) to 1.5 t/ha (Yamskaya Steppe); in the soil under the Huron forest plantation, it reaches 1.9 t/ha. These ranges of the rates of the C_{org} accumulation under the shelterbelts are in agreement with the results obtained by other authors. In particular, as shown by Isaev et al. [6], the annual sequestration of carbon by the ecosystems of shelterbelts after reaching the quasistationary regime of their functioning is estimated at 1.9 t/ha. Somewhat higher rates of organic matter accumulation observed by us in the soils of the recent forest plantation (the Huron key site) in comparison with the older shelterbelts (the key sites studied in Russia) may attest to a gradual slowing down of the humus-accumulative process under the shelterbelts. It is probable that the soil humus content will decrease in the soils under mature trees of the shelterbelts in the future. The study performed by Sauer et al. [32] showed that the intensity of the organic carbon sequestration in the topsoil (0–30 cm) under the artificial forest plantations increases in the first 30 years of growth of the trees and then decreases to zero values under 50-year-old trees. It is also known that the advancement of forests over steppe chernozems in the Late Holocene was accompanied by the transformation of chernozems into gray forest soils with lower reserves of organic matter [2, 20]. In 1930, the study of Tumin in the Kamennaya steppe showed that the accumulation of organic matter takes place under recently planted shelterbelts [16]. The studies performed in this area at the end of the 20th century and in the first decade of the 21st century did not show considerable differences between the pools of humus under the old shelterbelts and in the virgin soils [11, 12]. Therefore, the behavior of the organic carbon in the soils of the shelterbelts should be studied with due allowance for the age of the shelterbelt. The shelterbelts of different ages should be examined. As follows from our study, the positive influence of the shelterbelts on the humus state of the chernozems is clearly traced under the 55-year-old shelterbelts.

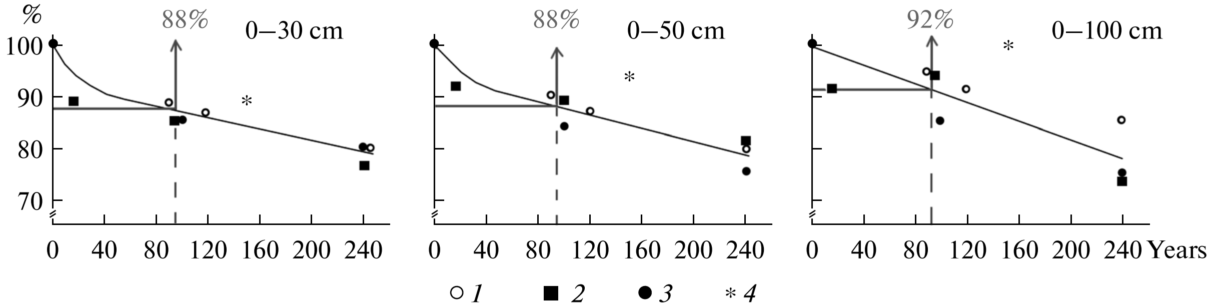

Fig. 4. Temporal changes in the pools of soil organic carbon upon plowing of the automorphic forest-steppe chernozems, % of the initial pools of C_{org} in the virgin soils (averaged values for key sites *1*, *2*, and *3* in Ivnyansk, Gubkin, and Prokhorovo districts of Belgorod oblast, respectively). The values above the arrows correspond to 95 years of soil cultivation. Asterisks (*4*) indicate the organic carbon pools in 150-year-old plowlands near the shelterbelts (averaged data from the Streletskaya Steppe, Yamskaya Steppe, and Kamennaya Steppe key sites).

CONCLUSIONS

Ecosystems of the artificially created shelterbelts and forest plantations in place of the former meadow and meadow-steppe landscapes of the forest-steppe zone of northern continents accumulate carbon in the organic matter of the soils.

In 55 years of the existence of shelterbelts on chernozems in the European part of Russia, the average annual rate of organic carbon sequestration in the upper soil meter has varied within 0.7–1.5 t/ha (at the Streletskaya Steppe, Yamskaya Steppe, and Kamennaya Steppe key sites). In 19 years of the existence of a forest plantation at the Huron key site in the United States, the average annual rate of organic carbon sequestration in the 1-m-deep Haplustoll of the Bonilla series has reached 1.9 t/ha.

A linear dependence between the observed changes in the thickness of the soil humus profiles under the shelterbelts (in comparison with the humus profiles of virgin soils) and the hydrothermic coefficient values has been found for the studied regions (the northeast of the Great Plains in the United States and the Central Russian Upland). The thickness of the soil humus layer (A1 + A1B horizons) under the shelterbelts increases by 10 cm per rise in the hydrothermic coefficient by 0.15. In the forest-steppe zone of European Russia, this corresponds to a shift by 50–100 km (75 km on average) in the northwestern direction.

A general tendency for the increase in the degree of humus accumulation in the upper 30 cm under the central parts of the shelterbelts in comparison with their peripheral parts has been observed. The C_{org} storage in this layer increases by 3.5–10.0 t/ha per each 10 m.

Observations over the development of the shelterbelts and the soils under them allow us to consider these ecosystems as specific natural–anthropogenic landscapes with certain stages in their development, definite interrelationships between their components, and specific sets of their properties and functioning processes. In light of the problem of global climate warming, the artificially created shelterbelts in the central forest-steppe zone of European Russia and in the northeast of the Great Plains in the United States serve as carbon sinks; i.e., they extract carbon from the carbon dioxide in the atmosphere and store it in the phytomass and in the soil organic matter. The sink function of the shelterbelts has been traced for several decades after their planting.

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REFERENCES

1. *Agroecological Conditions of Chernozems in the Central Chernozemic Region*, Ed. by A. P. Shcherbakov and I. I. Vasenev (Kursk, 1996) [in Russian].
2. A. L. Aleksandrovskii and E. I. Aleksandrovskaya, *Soil Evolution and the Geographic Environment* (Nauka, Moscow, 2005) [in Russian].
3. A. V. Al'benskii, “Forest reclamation and environmental changes,” Vestn. S–kh. Nauki (Moscow), No. 2, 96–101 (1961).
4. A. N. Gennadiev, A. P. Zhidkin, K. R. Olson, and V. L. Kachinskii, “Erosion and losses of soil organic carbon upon slope plowing,” Vestn. Mosk. Univ., Ser. 5: Geogr., No. 6, 32–38 (2010).
5. F. R. Zaidel'man, L. V. Stepantseva, A. S. Nikifirova, V. N. Krasin, S. B. Safronov, and T. V. Krasina, “Genesis and degradation of chernozems of European Russia under the impact of overmoistening,” in *Soil Protection and Reclamation Measures* (Kvarta, Voronezh, 2013) [in Russian].
6. A. S. Isaev, G. N. Korovin, V. I. Sukhikh, S. P. Titov, et al., *Environmental Problems of the Carbon Dioxide Sequestration via Reforestation and Afforestation* (Moscow, 1995) [in Russian].
7. V. V. Kaganov, “Changes in the ecosystem carbon pools upon afforestation in the steppe and semidesert zones of European Russia,” Probl. Reg. Ekol., No. 4, 7–12 (2012).
8. B. M. Kogut, N. A. Titova, and V. S. Buleeva, “Anthropogenic transformation of the qualitative composition of humus in chernozems of the Kamennaya Steppe,” Byull. Pochv. Inst. im. V.V. Dokuchaeva, No. 64, 41–49 (2009).
9. V. M. Kretinin, “Monitoring of soil fertility in agroforest landscape of the Central Russian forest-steppe,” Vestn. S–kh. Nauki (Moscow), No. 6, 45–49 (1991).
10. F. N. Lisetskii, “Soil-forming potential of forest plantations upon afforestation of sands in the forest-steppe and steppe zones,” Izv. Vyssh. Uchebn. Zaved., Lesn. Zh., No. 4. pp. 13-20. 2008.
11. F. N. Mil'kov, A. I. Nesterov, P. G. Petrov, B. I. Skachkov, et al., *Agroforest Landscapes of the Kamennaya Steppe* (Voronezh. Gos. Univ., Voronezh, 1992) [in Russian].
12. V. E. Prikhod'ko, Y. I. Cheverdin, and T. V. Titova, “Changes in the organic matter forms in chernozems of the Kamennaya Steppe under different land uses, locations, and hydromorphism degrees,” Eurasian Soil Sci., **46** (12), 1230–1240 (2013).
13. I. Yu. Savin and Yu. G. Chendev, “Dynamics of the humus content in plowed forest-steppe soils,” Pochvovedenie, No. 5, 88–92 (1994).
14. P. E. Solov'ev, *Influence of Forest Plantations on the Soil-Forming Process and Fertility of Steppe Soils* (Mosk. Gos. Univ., Moscow, 1967) [in Russian].
15. N. P. Sorokina, “Factors of differentiation and agrogenic transformation,” in *Kamennaya Steppe: Problems of the Soil Cover Study* (Pochv. Inst. im. V.V. Dokuchaeva, Moscow, 2007), pp. 97–120.
16. G. M. Tumin, *Influence of Shelterbelts on Soils in the Kamennaya Steppe* (Kommuna, Voronezh, 1930) [in Russian].

17. N. B. Khitrov, I. I. Lebedeva, Yu. I. Cheverdin, N. P. Chizhikova, and I. A. Yamnova, "Morphological features of soils in the Kamennaya Steppe," in *Kamennaya Steppe: Problems of the Soil Cover Study* (Pochv. Inst. im. V.V. Dokuchaeva, Moscow, 2007), pp. 36–71.

18. N. B. Khitrov and Yu. I. Cheverdin, "Distribution of seasonally overmoistened and waterlogged soils in the Kamennaya Steppe (in 2006)," in *Kamennaya Steppe: Problems of the Soil Cover Study* (Pochv. Inst. im. V.V. Dokuchaeva, Moscow, 2007), pp. 121–133.

19. N. B. Khitrov, Yu. I. Cheverdin, L. V. Rogovneva, and S. V. Natsentova, "Soil cover patterns on a gentle watershed slope under conditions of the modern seasonal overmoistening," in *Diversity of Soils in the Kamennaya Steppe* (Pochv. Inst. im. V.V. Dokuchaeva, Moscow, 2009), pp. 116-144.

20. Yu. G. Chendev, *Natural and Anthropogenic Evolution of Forest-Steppe Soils of the Central Russian Upland in the Holocene*, Doctoral (Geogr.) Diss. (Moscow, 2005).

21. Y. G. Chendev, L. L. Novykh, A. L. Aleksandrovskii, A. V. Dolgikh, O. S. Khokhlova, and L. G. Smirnova, "Anthropogenic evolution of dark gray forest-steppe soils in the southern part of the Central Russian Upland," Eurasian Soil Sci. **44** (1), 1–12 (2011).

22. Yu. G. Chendev, O. S. Khokhlova, and A. L. Aleksandrovskii, "Dehumification of automorphic chernozems in agrolandscapes of the central forest-steppe: intensity and stages," in Proc. Int. Conf. *Modern State of Chernozems* (Sept. 24–26, 2013, Rostov-on-Don) (Yuzh. Fed. Univ., Rostov-on-Don, 2013), pp. 350–352.

23. D. I. Shcheglov, *Chernozems of the Central Russian Plain and Their Evolution under the Impact of Natural and Anthropogenic Factors* (Nauka, Moscow, 1999) [in Russian].

24. J. R. Brandle, L. Hodges, and X. H. Zhou, "Windbreaks in North American agricultural systems," Agrofor. Syst. No. 61, 65–78 (2004).

25. Yu. G. Chendev, C. L. Burras, and T. J. Sauer, "Transformation of forest soils in Iowa (United States) under the impact of long-term agricultural development," Eurasian Soil Sci. **45** (4), 357–367 (2012).

26. J. Kort, "Benefits of windbreaks to field and forage crops," Agric. Ecosyst. Environ. **22/23**, 165–190 (1988).

27. K. R. Olson, A. N. Gennadiyev, A. P. Zhidkin, M. V. Markelov, V. N. Golosov, and J. M. Lang, "Use of magnetic tracer and radio-cesium methods to determine past cropland soil erosion amounts and rates," Catena **104**, 103–110 (2013).

28. C. H. Perry, C. W. Woodall, G. C. Liknes, and M. M. Schoeneberger, "Filling the gap: improving estimates of working tree resources in agricultural landscapes," Agrofor. Syst. **75** (1), 91–101 (2009).

29. R. A. Read, *The Great Plains Shelterbelt in 1954 (A Re-Evaluation of Field Windbreaks Planted between 1935 and 1942 and a Suggested Research Program)* (Great Plains Agric. Council Publ., Lincoln, NE, 1958), No. 16.

30. T. J. Sauer, C. A. Cambardella, and R. B. Brandle, "Soil carbon and tree litter dynamics in a red cedar–scotch pine shelterbelt," Agrofor. Syst. **71**, 163–174 (2007).

31. T. J. Sauer and M. P. Nelson, "Science, ethics, and the historical roots of our ecological crisis: was white right?" in *Sustaining Soil Productivity in Response to Global Climate Change. Science, Policy, and Ethics* (Wiley-Blackwell, Chichester, UK, 2011), pp. 3–16.

32. T. J. Sauer, D. E. James, C. A. Cambardella, and G. Hernandez-Ramirez, "Soil properties following restoration or afforestation of marginal cropland," Plant Soil **360** (1–2), 2012.

33. U.S. Forest Service, *Possibilities of Shelterbelt Planting in the Plains Region. Special Publication* (Lake States For. Exp. Stn., 1935).

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