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ORIGINAL PAPER

Impact of plant species on the formation of carbon and nitrogen stock in soils under semi-desert conditions

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Abstract The unique forest ecosystems investigated were created on the place of natural steppe biogeocoenoses 60 years ago. The aim of the study was to elucidate the effect of plant species on the formation of organic C and N stocks in soils and to estimate nitrogen availability for artificial wood plantation. For this purpose, 290 soil samples were taken from four forest monocultures (*Quercus robur* L., *Pinus sylvestris* L., *Cotinus coggygria Scop.,* and *Acer tataricum* L.) and from virgin steppe ecosystem. The amounts and stocks of organic C, total and readily nitrified N, and seasonal dynamics of NO_3^- and NH_4^+ ions activities were determined. It was shown that the species composition of the stands influenced the stock of organic C and N in soils. The storages of C and total N differed by 74 and 4.4 Mg/ha^{-1}, respectively, in the litter and upper horizons (0–40-cm layer) in the stands studied. The differences in distribution of stocks of these elements in virgin steppe and artificial forest ecosystems were found. Organic C and N stocks increased 1.6–6.6 times in the forest litter compared to the steppe one, while in 5–40-cm layer, the storages of C and N decreased by 20–35% compared to the virgin soil. The impact of litter on total N content in arid climate was limited in 0–5-cm layer. The deficit of mineral N compounds was observed in autumn in soil with low stock of total N.

Keywords Afforestation · Semi-desert zone · Carbon nitrogen dynamics in soil

Introduction

The key aspect of investigation of C and N cycles in biosphere is the fixation of these elements in soil organic matter (Kurganova et al. 2010). It was shown that accurate estimation of C and N accumulation in soils under wood plantations compared to virgin steppe soils should be based on the distribution of their storages in the whole upper horizon (0–40 cm). Comparison of soils under wood plantations and steppe or meadow vegetation based on storages of C and N in the litter and up-layer of humus horizon may lead to overestimation of the role of forest ecosystems in accumulation of these biophilic elements in soil.

Carbon and nitrogen cycles changed significantly in artificial wooden stands compared to natural ecosystems, even when native vegetation was presented by tree species (Gartzia-Bengoetxea et al. 2009). The increase in C stocks was found in a result of conversion of arable land to the forest (Jandl et al. 2007; Johnson 1992; Post and Kwon 2000). The increase of C stocks was explained by the increase in its input in plant residues and decrease of CO_2 losses in the former ploughed layer. On the contrary, the surface layers of cultivated agricultural soils had 30–35% less C than forest soil, as was observed, for example, in Ontario (Ellert and Gregorich 1996) and 50% less N stocks as was observed in northern Cis-Caspian lowland (Kulakova 2010).

Meanwhile, the changes in the soils under the impact of stands depended on a number of factors, including the age of plantation (Karhu et al. 2011). The study of the influence of various plant species on the soils showed that most

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clearly influenced soil property was organic carbon content (Quideau et al. 2001; Pérez-Bejarano et al. 2010). The substitution of natural forests in semi-arid environment by stands resulted in the degradation of physical properties and decreased organic carbon content in soils (Maestre and Cortina 2004). The differences were found in the degree of litter decomposition consisted of various plant species and types (Cornelissen 1996). That was related to chemical composition of the litter and the structure of microbial communities responsible for the litter decomposition (Strickland et al. 2009). Climate was also very important factor that influenced chemical composition of plants of the same species. For instance, N content in 2–3-year-old pine needles from the pines grown on N insured soils varied from 0.62 to 0.74% in automorphic environment and from 1.1 to1.5% in hydromorphic one (Breusova 1984). Sariyildiz et al. (2005) showed that even the topographic position (position at the slope and exposition) was significant for the rate of decomposition of the litter under *Quercus robur* and *Pinus sylvestris*: lignin content and lignin/C ratio were much higher in the southern slopes than on the northern ones. Climatic parameters (total precipitation and absolute maximum temperature) had the strongest influence on the litter production under the oak stands (Díaz-Maroto and Vila-Lameiro 2006) and therefore on soil properties.

The ecosystems studied were established in the semi-desert zone on the place of virgin steppe biogeocoenoses existed in azonal environment due to seasonally available ground waters. Such plant species as *Quercus robur* L., *Pinus sylvestris* L., *Cotinus coggygria Scop.*, and *Acer tataricum* L. were very common in the steppe part of Ukraine and south of Russia for the organization of field-protective belts and massive stands since the end of the nineteenth century. The pine and oak impact on Chernozems was well investigated. The change of steppe vegetation to 28–32-year-old linear or massive stands of *Quercus robur* L. and *Pinus sylvestris* L. led to the increase in total C and N stocks in 1-m layer of Chernozems of various texture (Kretinin et al. 1995). We did not find any data on *Cotinus* and *Acer* impact to C and N contents in the soil as these plants did not form pure stands, and more often were in the combination with other bushes (Shatalov 2000) or formed the shrub layer in natural forests (Misik and Kárász 2010), or stands (Nikitin 1966).

Relatively few information is available on the impact of different plant species on soils in semi-desert climatic zone under sufficient moisture content. Kastanozems are the most fertile in semi-desert and occupy about 15–20% of total area. Therefore, the estimation of soil fertility under wood stands is an important task. On the other hand, sufficient N supply of plants in conditions of sufficient moisture promotes their growth and prevents the downfall from bacterial diseases (Olovyannikova and Lindeman 2000).

This study was aimed to investigate (1) the effect of different plant species on the formation of organic C and N stocks in soils compared to the steppe vegetation and (2) N availability for the artificial wood plantation.

Materials and methods

Study sites

The area studied was located in the clayey semi-desert of the northern Cis-Caspian lowland (Volgograd region, Russia, 49°25′N 46°46′E). The climate was arid continental; mean annual precipitation was about 298 mm year^{-1} that was almost three times less than evaporation—900–1,000 mm year^{-1} (Sapanov 2003). The generally plain territory had well-developed mesorelief. Mesodepressions occupied about 15% of total area. Their sizes reached several hectares with the depth up to 100–150 cm. Kastanozems with steppe type of vegetation were leached from readily soluble salts; they were underlayed by the lenses of fresh water. The bottoms of the large depressions with the same catchment area had similar environment for pedogenesis: loess carbonaceous loamy as a parent material, steppe type of vegetation, and same moistening. As a result, the soils of these depressions had little differences and were very similar: same profile and thickness of humus accumulative horizon about 40 cm, effervescence at the depth of 75 cm, and pH 6.7–6.9 (Rode and Pol'skiy 1960). Cultivation of large forest areas without irrigation was possible only on Kastanozems soils within these depressions. Unique forest ecosystems were created in Dzhanybek Research Station (Institute of Forest Science RAS). We investigated the soils of two depressions: one depression with steppe vegetation and *Quercus robur* L. and *Pinus sylvestris* L. stands, and the other depression with plantations of *Cotinus coggygria Scop.* and *Acer tataricum* L. The sites in each depression were located very close to each other, at the distance no more than 30 m. This allowed us to state that the pristine soil texture from different soil horizons and other soil properties were exactly the same.

The ecosystems studied were established on the place of virgin steppe biogeocoenoses 60 years ago. We investigated soils under four forest species, *Quercus robur* L., *Pinus sylvestris* L., *Cotinus coggygria Scop.*, and *Acer tataricum* L., and under virgin steppe vegetation. The distance between the rows was 2 m; the space between trees in the row was 1.5 m. The earthworm introduction into oak stand soil was done more than 40 years ago. Their abundance by now was between 20 and 80 units per square

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meter, depending the season (Vsevolodova-Perel' et al. 2010), and they did not occupy others stands. The introduced *Eisenia nordenskioldi* worms belonged to the group of pigmented soil-litter worms fed by leaf litter mixing it together with mineral part of soil, which led to double increase in the rate of litter decomposition (Perel' 1979). As a result, the upper part of humus horizon in the soil under *Quercus* stands (mainly 0 to 3–5 cm depth) had well-expressed coprogenic structure.

Sampling and soil analyses

The samples were taken from two layers of the litter (*L* and F-H) and from the soil profiles on the depths 0–5, 5–10, 10–20 cm and deeper from each 10 cm down to 60 cm. The samples were taken in six replicates for the measurement of organic C content, in four replicates for the measurement of NO_3^- and NH_4^+ ions activities, and in six replicates for the measurement of total N down to the depth of 40 cm. Samples for the analyses of readily nitrified N were taken in four replicates from the litter (*L* and F-H layers were mixed together) and the upper layer of humus horizon (0–5 cm). Samples for the measurement of ions activity were taken in spring and autumn. All other analyses were performed in the specimens sampled in spring. Soil organic C was determined by wet combustion with potassium dichromate (Vorobiova 1988); the wet combustion method was used for total N determination (Kjeldahl's method as described by Vorobiova 1988). The activity of NO_3^- and NH_4^+ ions was measured in water suspensions of soil (soil/water 1:5, w/w) using pH tester with membrane electrode "Alit." To determine readily nitrified N, the soils were composted during 1 month at 25°C and at 60% of water-holding capacity. The readily nitrified N was calculated from maxima pattern during composting. Litter stocks were determined in quintuple repetition using the 40 × 40 cm plots at each site; annual litter fall was determined under *Quercus* and *Acer* at 1-m^2 plots during two seasons in autumn 2008 and 2009. All litter or annual litter fall material was homogenized by milling and mixing up to the size of the particles ≤1 cm. The part of this specimen was taken for further grinding up to 0.1-mm size. The stocks were calculated using the bulk density of a layer. Soil moisture content was determined after the drying at 105°C. Mean values and confidence interval (CI) at $P < 0.05$ were given in tables.

Results

Litter composition, organic matter storage in litter, and litter production

All kinds of litter (steppe and forest) visually could be divided into two parts: upper litter (*L*) made of poorly decomposed plant debris (mainly poorly transformed leaves, grass stems, or pine needles), and lower litter (F-H), consisting of better decomposed material (small leaves or grass fragments, peat-like brown material in forest and dark-gray silt material in steppe litter).

The highest values of organic matter (OM) were found under *Cotinus*, *Acer tataricum, and Pinus Sylvestris*, 276, 275, and 227 Mg ha^{-1} dry matter (DM), respectively (Table 1). The stocks of steppe litter were also high due to the absence of grazing; however, they were 3.6 times less than under pine, and 4.4 times less than under *Cotinus* and *Acer,* and did not differed significantly from the stock of litter under *Quercus* plantation.

The litter input in the artificial forest ecosystems was 3.55 ± 0.60 Mg ha^{-1} $year^{-1}$ DM under *Quercus* stands and 4.10 ± 0.95 under *Aser* plantation with $P < 0.05$ and $n = 8$ (Table 1).

Organic C content and storage in soils

The carbon content regularly decreased with depth along the profile in all sites (Table 2). The *L* layer of the forest litter under oak, pine, and maple stands had no reliable differences in C contents compared to the steppe site (267 and 279–27 g C kg^{-1} of soil). Significant decrease in C content relatively to the

Table 1 The stock of organic matter in different layers of litter and litter production (DM, (Mg/ha^{-1}))

Vegetation	Steppe ecosystem	*Quercus robur*	*Pinus sylvestris*	*Cotinus coggygria*	*Acer tataricum*
Litter					
L	19.60 ± 2.02[a]	60.75 ± 6.42[b]	43.00 ± 3.54[c]	50.70 ± 4.78[bc]	246.50 ± 28.83[d]
F-H	42.80 ± 5.43[a]	14.53 ± 2.46[b]	184.35 ± 19.80[c]	225.50 ± 40.65[c]	28.50 ± 5.63[d]
Total	62.40	75.28	227.35	276.19	275.00
Aboveground production	3.15 ± 0.20*[a]	3.55 ± 0.6[ab]	Not determined	Not determined	4.10 ± 1.0[b]
Litter's stock/aboveground production	20	21			67

The data marked by different letters denote a significant difference at $P < 0.05$

* The date from Sizemskaya and Sapanov (2010)

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Table 2 The content of organic C (g kg^{-1} of soil) in Kastanozems in forest and steppe ecosystems, (±CI), $n = 6$, $P \leq 0.05$

Layer, cm	Vegetation				
	Steppe vegetation	*Quercus robur*	*Pinus sylvestris*	*Cotinus coggygria*	*Acer tataricum*
L	266.6 ± 19.8^{ab}	279.2 ± 31.5^{ab}	327.4 ± 52.0^{a}	176.6 ± 32.3^{d}	231.2 ± 24.5^{b}
F-H	95.7 ± 13.5^{a}	211.0 ± 42.1^{b}	159.6 ± 19.5^{b}	164.6 ± 16.8^{b}	160.3 ± 26.2^{b}
0–5	48.8 ± 8.9^{a}	103.2 ± 16.5^{d}	172.0 ± 37.6^{b}	160.5 ± 5.5^{b}	34.1 ± 2.3^{a}
5–10	27.8 ± 2.2^{a}	25.1 ± 2.2^{a}	23.1 ± 3.9^{a}	23.3 ± 1.7^{a}	18.5 ± 1.4^{b}
10–20	19.9 ± 1.7^{a}	16.7 ± 0.9^{a}	17.6 ± 1.5^{a}	17.1 ± 1.2^{a}	15.7 ± 1.0^{b}
20–30	18.3 ± 2.4^{a}	13.9 ± 2.8^{a,b}	12.7 ± 1.6^{b}	15.6 ± 3.1$^{a\ b}$	16.7 ± 3.0^{a,b}
30–40	11.8 ± 2.7^{a}	7.0 ± 0.9^{b,d}	5.6 ± 1.2^{b}	8.0 ± 0.9^{d}	8.4 ± 0.7^{d}
40–50	7.2 ± 1.2^{a}	5.7 ± 0.2^{b}	7.0 ± 1.0^{a}	5.8 ± 0.5^{ab}	6.2 ± 1.0^{ab}
50–60	6.0 ± 0.6^{a}	4.3 ± 0.6^{b}	5.3 ± 0.2^{a}	4.0 ± 0.3^{b}	5.5 ± 1.1^{ab}

The data marked by different letters denote a significant difference at $P < 0.05$

Table 3 The stock of organic C (Mg/ha^{-1}) in Kastanozems in the forest and steppe ecosystems, (±CI, $n = 6$, $P \leq 0.05$)

Layer, cm	Vegetation				
	Steppe ecosystem	*Quercus robur*	*Pinus sylvestris*	*Cotinus coggygria*	*Acer tataricum*
L	5.2 ± 0.5^{a}	17.0 ± 1.8^{b}	14.1 ± 2.2^{b}	9.0 ± 1.6^{c}	57.0 ± 6.7^{d}
F-H	4.1 ± 0.5^{ad}	3.1 ± 0.5^{a}	29.4 ± 3.2^{c}	37.0 ± 6.1^{c}	4.6 ± 0.9^{d}
0–5	26.8 ± 4.5^{a}	45.4 ± 8.3^{b}	92.0 ± 18.8^{c}	91.4 ± 2.6^{c}	20.1 ± 1.2^{d}
5–10	15.4 ± 0.6^{a}	13.9 ± 0.6^{b}	12.9 ± 1.0^{bc}	12.7 ± 0.5^{c}	10.9 ± 0.4^{d}
10–20	22.9 ± 0.9^{a}	19.7 ± 0.5^{bc}	20.6 ± 0.8^{b}	20.0 ± 0.6^{b}	18.7 ± 0.5^{c}
20–30	23.6 ± 1.2^{a}	17.9 ± 1.0^{bc}	16.4 ± 0.8^{b}	20.1 ± 1.6^{cd}	21.5 ± 1.5^{ad}
30–40	16.3 ± 1.4^{a}	9.7 ± 0.5^{b}	7.7 ± 0.6^{c}	11.0 ± 0.5^{d}	11.6 ± 0.4^{d}
40–50	10.6 ± 0.6^{a}	8.4 ± 0.1^{b}	10.3 ± 0.5^{a}	8.5 ± 0.3^{bc}	9.1 ± 0.5^{c}
50–60	9.1 ± 0.3^{a}	6.5 ± 0.3^{b}	8.1 ± 0.1^{c}	6.1 ± 0.2^{b}	8.4 ± 0.6^{ac}
Litter	9.3	20.1	43.5	46.0	61.6
5–60	97.9	76.1	76.0	78.4	80.2
Total	134.0	141.6	211.5	215.8	161.9

The data marked by different letters denote a significant difference at $P < 0.05$

steppe *L*-litter was observed under fustic (*Cotinus coggygria*) plantation (177 g C kg^{-1}). C contents were significantly higher (1.7–2.2 times) in the lower part of litters of the forest sites compared to the steppe ones.

The upper 5-cm layer of the humus horizon had the most variable C contents in different sites. It was similar in the steppe site and under maple stand and was 2–3.5 times higher in oak, pine, and fustic stands. The differences in C content continued to stay important at a depth 5–10 cm between maple site and other sites (steppe, *Cotinus*, *Acer,* and *Quercus)* sites. C content was 1.5 times less than in the steppe site and 1.3–1.4 times less than in forest sites. The trend for the deeper part of profiles was as following. C content was always higher in the steppe site than in forest ones. This regularity was not proved statistically even for all layers of the forest soils. It was most expressed for the depth 30–40 cm, and under the steppe vegetation, C content was 1.4–2 times higher than in forest sites.

In litter and in 0–60-cm layer in *Quercus robur* stand, the storage was equal to natural ecosystems, while in *Cotinus coggygria* and *Pinus sylvestris* plantations, it increased by 58–61%. In *Acer tataricum* stand, the total C stock increased by 21% compared to the virgin soil.

In litter under *Quercus,* total C stock was about 2 times higher than in steppe litter (Table 3). In litter under *Cotinus* and *Pinus*, it was about 4.7–5 times higher compared to the steppe litter. In *Acer* plantation, the stock in litter was about 6.6 times higher than under native vegetation.

In 0–5-cm layer, the significant increase in organic C stock was observed under *Cotinus* and *Pinus* stand, it was 3–5 times higher compared to the steppe and other forest ecosystems. In the oak plantation in this layer, C stocks were 1.7 times higher than in the steppe plot, while in the Acer plantation, they were 1.3 times less.

C storage in the litter and up-layer of humus horizon of soil (0–5 cm) under *Quercus*, *Pinus, Cotinus,* and *Acer*

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Table 4 The content of total N (g kg^{-1} of soil) in Kastanozems in the forest and steppe ecosystems, (±CI), $n = 6$, $P \leq 0.05$

Layer, cm	Vegetation				
	Steppe ecosystem	*Quercus robur*	*Pinus sylvestris*	*Cotinus coggygria*	*Acer tataricum*
L	17.9 ± 1.5^{a}	15.5 ± 1.7^{ad}	12.9 ± 0.5^{b}	13.7 ± 0.7^{bd}	14.3 ± 0.9^{bd}
F-H	8.5 ± 1.2^{a}	13.9 ± 1.8^{b}	8.8 ± 0.5^{a}	11.5 ± 0.9^{ab}	11.3 ± 0.9^{b}
0–5	4.5 ± 0.7^{a}	7.9 ± 0.8^{b}	9.0 ± 0.8^{bd}	10.4 ± 0.6^{d}	2.3 ± 0.1^{c}
5–10	2.6 ± 0.2^{a}	2.1 ± 0.1^{b}	1.6 ± 0.2^{d}	1.8 ± 0.1^{d}	1.8 ± 0.2^{d}
10–20	2.3 ± 0.1^{a}	1.6 ± 0.2^{bd}	1.5 ± 0.1^{b}	1.6 ± 0.1^{bd}	1.8 ± 0.1^{d}
20–30	1.8 ± 0.1^{a}	1.5 ± 0.1^{b}	1.3 ± 0.1^{d}	1.5 ± 0.1^{b}	1.5 ± 0.1^{b}
30–40	1.1 ± 0.1^{a}	0.9 ± 0.1^{a}	0.6 ± 0.1^{b}	0.9 ± 0.1^{a}	0.9 ± 0.1^{a}

The data marked by different letters denote a significant difference at $P < 0.05$

Table 5 The stock of total N (Mg ha^{-1}) in Kastanozems in the forest and steppe ecosystems, (±CI, $n = 6$, $P \leq 0.05$)

Layer, cm	Vegetation				
	Steppe ecosystem	*Quercus robur*	*Pinus sylvestris*	*Cotinus coggygria*	*Acer tataricum*
L	0.35 ± 0.04a	0.94 ± 0.10b	0.55 ± 0.05c	0.69 ± 0.07d	3.52 ± 0.41e
F-H	0.36 ± 0.05^{a}	0.20 ± 0.03^{b}	1.62 ± 0.17^{c}	2.58 ± 0.47^{d}	0.32 ± 0.06^{a}
0–5	2.48 ± 0.39^{a}	3.48 ± 0.18^{b}	4.82 ± 0.22^{c}	5.93 ± 0.42^{d}	1.35 ± 0.12^{e}
5–10	1.44 ± 0.11^{a}	1.17 ± 0.06^{b}	0.89 ± 0.11^{c}	0.98 ± 0.06^{d}	1.06 ± 0.10^{bc}
10–20	2.65 ± 0.12^{a}	1.89 ± 0.24^{b}	1.76 ± 0.11^{b}	1.87 ± 0.12^{b}	2.14 ± 0.12^{c}
20–30	2.32 ± 0.13^{a}	1.94 ± 0.10^{b}	1.68 ± 0.08^{c}	1.94 ± 0.13^{b}	1.94 ± 0.12^{b}
30–40	1.52 ± 0.11^{a}	1.24 ± 0.09^{b}	0.83 ± 0.10^{c}	1.24 ± 0.06^{b}	1.24 ± 0.08^{b}
Litter	0.71	1.14	2.17	3.27	3.84
5–40	7.93	6.24	5.16	6.03	6.38
Total	11.12	10.86	12.15	15.23	11.57

The data marked by different letters denote a significant difference at $P < 0.05$

plantations was higher compared to steppe soils by 81, 275, 280, and 126%, respectively.

Significant losses of organic C stock in forest soils were recorded in most layers at the depth 5–60 cm compared to the steppe soil. In forest soils in this layer, the losses reached 18–22%.

Total N content and storage in soils

Total N content decreased regularly along the profile of Kastanozems (Table 4). In *L* layer of litter, total N content was lower in wood stands compared to the steppe ecosystem. Significant differences were found between steppe site versus *Pinus*, *Acer,* and *Cotinus* stands. N content in the bottom part of the litter was quite different: it was higher in the forest F-H layers compared to the steppe layer. Significant differences were found between steppe site and *Quercus* and *Acer* stands. The highest differences were observed between the sites of *Quercus* plantation and steppe vegetation.

In 0–5-cm layer, N content in soils under oak, pine, and fustic stands was about 2 times higher, and in the soil under *Acer* stand about 2 times lower compared to the steppe soil. At the depth 5–40 cm in forest soils, N content was generally significantly lower compared to the steppe soil.

N storage in the litter and humus accumulative horizon of soil (0–40 cm) was similar in all sits except for *Cotinus* plantation. The storage values in this stand were higher by 20–29% compared to other plots.

N stock in the steppe litter was about 6% of that in the litter and upper horizon (0–40) cm and was 1.6–5.4 times less than in forest litters (Table 5). N stock in litter reached 11% of total N stock in the litter and upper horizon (0–40 cm) in *Quercus robur* stand, 18% in *Pinus sylvestris* plantation, 22% in *Cotinus coggygria* stand, and 33% in *Acer tataricum* stand. In the upper horizon (0–40 cm), N stock increased in *Cotinus* stand (by 15%) and decreased in *Acer* stand (by 26%) compared to the steppe ecosystem. No valid differences were found between N stock in steppe soils and soils under oak and pine. The redistribution of N stock was found within these horizons

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Table 6 The content of readily nitrified N compounds (mg $N(NO_3^-)$ kg^{-1}, numerator) and their stock (g m^{-2}, denominator) (±CI) in Kastanozems, calculated from the pattern maxima during 1-month composting, $n = 4$, $P \leq 0.05$

Layer	Vegetation				
	Steppe ecosystem	*Quercus robur*	*Pinus sylvestris*	*Cotinus coggygria*	*Acer tataricum*
Litter	1.85 ± 0.12[a]	2.41 ± 0.21[b]	3.05 ± 0.28[c]	1.68 ± 0.10[a]	2.95 ± 0.12[c]
	1.15	1.82	6.93	4.62	8.11
0–5 cm	2.34 ± 0.12[a]	2.96 ± 0.16[b]	2.25 ± 0.14[a]	4.41 ± 0.25[c]	2.31 ± 0.10[a]
	6.48	7.4	6.17	12.34	6.45

The data marked by different letters denote a significant difference at $P < 0.05$

in soils under wood stands. In the upper 5-cm layer, N stocks were 1.4–2.4 times higher in all forest sites compared to steppe soils except for *Acer*: N stocks in soil under this plantation were 1.8 times lower. N storage in the litter and up-layer horizon of soil (0–5 cm) under *Quercus*, *Pinus, Cotinus*, and *Acer* plantations was higher compared to steppe soils by 45, 119, 188, and 63%, respectively. In *Quercus*, *Pinus, Cotinus,* and *Acer* plantations at the depth 5–40 cm, N storages were lower compared to steppe soils by 21, 35, 24, and 20%, respectively.

The content of readily nitrified N compounds

The content of readily nitrified N compounds was much higher (1.3–1.6 times) in the forest litters than in the steppe one (Table 6), except for *Cotinus* stand, where the concentration of readily nitrified N was similar to the steppe plot.

The content of readily nitrified N compounds was 2.34 mg $N(NO_3^-)$ kg^{-1} in upper horizon (0–5 cm) of the steppe soil. Similar values were observed in soils under *Pinus* and *Acer* stands. The contents of readily nitrified N compounds were 1.9 and 1.3 times higher in *Cotinus* and *Quercus* stands compared to the steppe soil (Table 6).

The stock of readily nitrified N compounds in litters under *Quercus, Cotinus*, *Pinus*, and *Acer* stands was 1.6, 4.0, 6, and 7 times higher compared to the steppe litter (1.15 g m^{-2}).

The stock in 0–5-cm layer did not differed in various ecosystems except for *Cotinus* stand (Table 6), where the stocks were 1.7–2 times higher compared to other ecosystems. This was due to higher content of readily nitrified N compounds in this layer.

Values of NO_3^- and NH_4^+ ions activities

The activities of NO_3^- and NH_4^+ ions in the litters and soils varied in a wide range from 19.25 to 0.04 mol/l × 10^{-4} for NO_3^- ions and from 6.30 to 0.05 mol/l × 10^{-4} for NH_4^+ ions. Nevertheless, the same tendency of distribution of ions activities was observed in the soils investigated.

Values of NO_3^- ions activities as often as not were higher than those of NH_4^+ ions (Fig. 1). Activities of NO_3^- ions in spring were 2–25 times higher than activities of NH_4^+ ions (Fig. 1-I). Only in litter under *Cotinus* stand, NO_3^-/NH_4^+ activities ratio was lower than unity. In autumn, the values varied from 2 to 5 in litters and upper horizons (40 cm) of soils (Fig. 1-II). At this period, the ratio of NO_3^-/NH_4^+ activities was less than 1 only in this horizon under *Acer* stand and at the depth 10–40 cm under *Cotinus* stand. This fact was connected with extremely low values of NO_3^- activities (Fig. 1-IIa).

In the litters, values of NO_3^- and NH_4^+ ions activities were constantly several times higher compared to humus horizons and subsoil (Fig. 1). The lowest values of activities were in the litters in *Pinus* stand.

Maximal values of NO_3^- activities were observed in spring under *Ace*r stand. In autumn, the values of NO_3^- activities in upper horizons in this site were considerably lower compared to other sites.

C/N ratio

As a rule C/N ratio values decreased along the profiles (Table 7). It was shown that organic matter of the litter was more enriched by nitrogen in the steppe site than in the forest. Exception was *L* layer of fustic plantation, where the ratio was somewhat lower than in the *L* layer of the steppe litter (12.9 and 14.9, respectively). The highest values of C/N ratio in litter were marked in *L* layer of *Pinus* stand—25.4. Humus of up soil layer was less enriched with nitrogen on the steppe plot compared to the forest ones. At the depth 0–5 cm in forest soils, C/N values changed from 13.1 to 19.1 and in steppe soil were about 10.8.

Down the soil profile, the C/N values were rather similar in all plots. However, on the depth 30–40 cm, soil organic matter under the steppe vegetation was less enriched with N compared to the forest plots (C/N changed from 7.8 to 9.3 under the stands and was 10.7 on the steppe plot). Less enriched humus was observed in the soil under the pine plantation down to the depth 20 cm.

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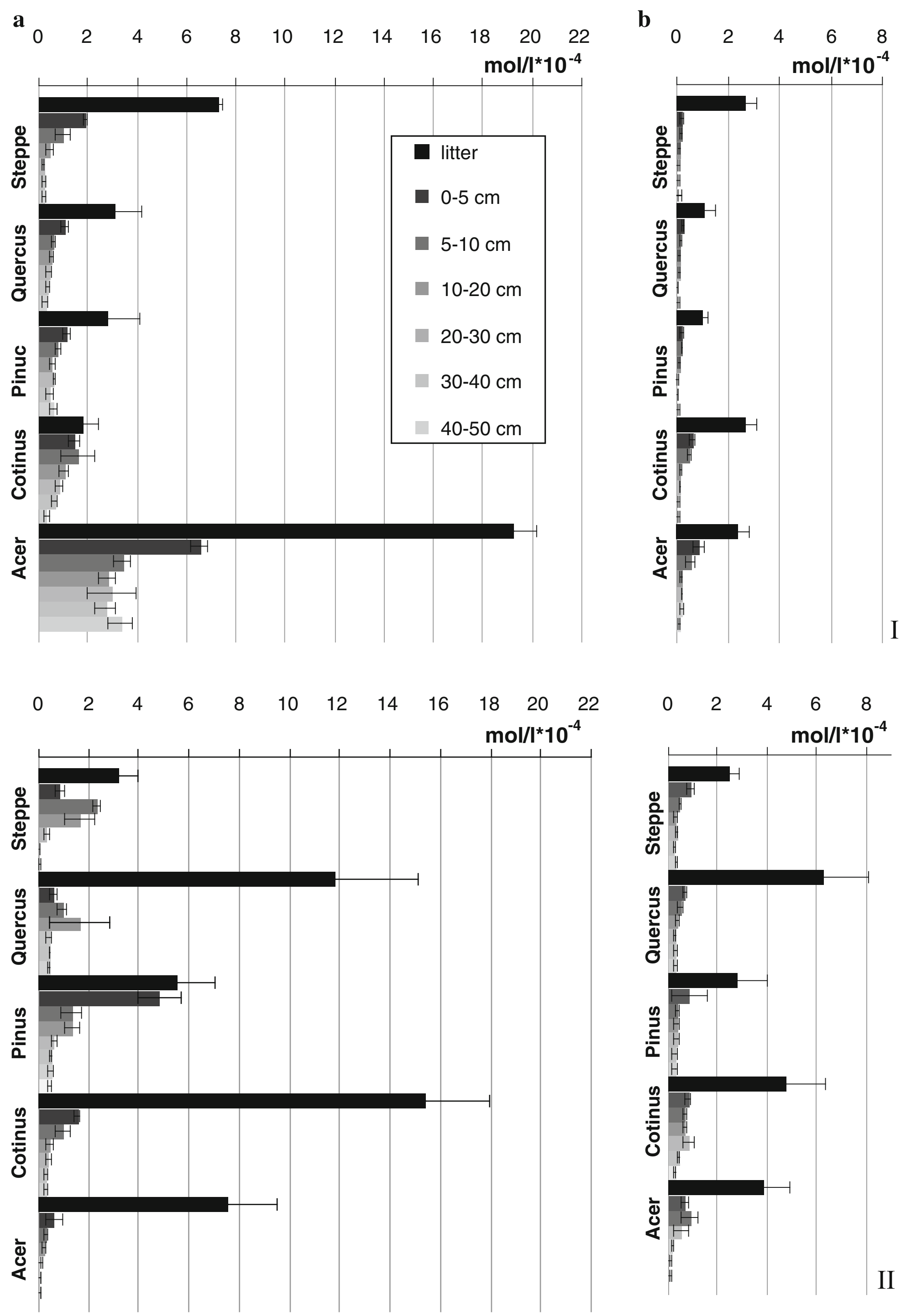

Fig. 1 Values of NO_3^- *a* and NH_4^+ *b* ions activities; **I** in spring. **II** in autumn

Discussion

The formation of organic C, total and available N stocks in soils under similar climate, and position in the relief depended on the peculiarities of biological cycling, and particularly on the income of organic residues and the rate of their decomposition. It was previously noted that the litters formed in the plantations of Dzhanybek station had high stock of OM (Rzheznikova et al. 1992).

Formation of organic C and N stocks in the litter

It was shown (Balboa-Murias et al. 2006) that C stock in the litter reached 16% of total C stock in the litter and soil

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Table 7 C/N values in Kastanozems in the forest and steppe ecosystems

Layer, cm	Vegetation				
	Steppe ecosystem	*Quercus robur*	*Pinus sylvestris*	*Cotinus coggygria*	*Acer tataricum*
L	14.9	18	25.4	12.9	16.2
F-H	11.3	15.2	18.1	14.3	14.2
0–5	10.8	13.1	19.1	15.4	14.8
5–10	10.7	12	14.4	12.9	10.3
10–20	8.7	10.4	11.7	10.7	8.7
20–30	10.2	9.3	9.8	10.4	11.1
30–40	10.7	7.8	9.3	8.9	9.3

in virgin *Quercus robur* stands in NW Spain. C stock in the litter reached 14% of total C stock in the litter and upper horizon (0–60 cm) in *Quercus robur* stand and reached 21% in *Pinus sylvestris* and *Cotinus coggygria* plantations. The share of the litter in the total C stock was highest in *Acer tataricum* stand and amounted to 38%. In steppe litter, C stock amounted to 7%.

The litter input on the soil surface was very similar both in the steppe and under the forest species—3.00–3.30 Mg ha^{-1} year^{-1} DM in herb-grass associations (Sizemskaya and Sapanov 2010) (Table 1). This meant that the accumulation of litter was mostly influenced by the rate of its decomposition.

The mean residence time (MRT) for the litter (the ratio of OM stock in litter to annual litter fall) was measured in steppe biocoenosis, *Quercus,* and *Aser* stands. The MRT values obtained were 20 for the steppe biocoenosis, 21 for *Quercus*, and 67 for *Aser* plantations and were significantly less compared to the rate of decomposition in same ecosystems of forest-steppe zone. That corresponded to slow rate of litter decomposition in drier conditions (Pausas 1997). To compare, the MRT of litter in 60-year-old oak forest was 13 years (Tellerman's experimental forest station, Voronezh region; 111°20′53″N, 41°58′35″E; Molchanov 1975). MRT in the steppe community in the steppe zone was 13 times less—1.5–1.6 years (Rodin and Bazilevich 1965).

The lowest rate of litter decomposition was observed under *Acer tataricum* plantation (Table 1). The rate was three times slower compared to the oak stand. Our results agreed well with experimental data on slower degradation of *Acer tataricum* litter fall compared to *Quercus robur* (Sokolov 1960). In addition, the more rapid degradation of *Quercus* litter resulted from introduction of *Eisenia nordenskioldi* worms into the oak stands and effective transformation of the litter material.

According to McClaugherty and Berg (1987) and Martin et al. (1996), the primary leaching of most labile compounds, decomposition of starch and amino acids corresponded to the first phase of litter decomposition. The second stage included the decomposition of more stable compounds. Apparently, the first stage of decomposition affected the *L* layer, while the second, the F-H layer. Thus, the ratio between OM in *L* and F-H layers could characterize the relationship between the rates of different phases of decomposition. This ratio was higher in the steppe site compared to *Pinus and Cotinus* stands—0.5 and 0.2, respectively. The lower part of the litter under *Quercus* stands was actively transformed by the worms, and apparently, this was the reason for high values of stock ratio for the upper and lower layers—4.2 (Table 1). The litter under the *Acer* stands consisted mostly (9/10) of poorly decomposed material that indicated slow processes of the later stages of litter decomposition.

In litter C concentrations determined the values of C/N ratio (Table 7). The correlation coefficient between C/N ratio and C concentration was 0.87 ($P = 0.05$; $n = 5$) in the *L*-litter of all stands. N concentrations were less important for C/N values.

C/N ratios influenced the rate of litter decomposition (Manzoni and Porporato 2007; Manzoni et al. 2010); however, it was shown that this index had not widespread applicability to all litter types (Thomas and Prescott 2000). The relationship between the decomposition rate and C/N ratio or N concentration in litter depended on organic matter quality and the stage of decomposition. Nutrients in mineral forms were taken up (immobilized) by the decomposers and thus accumulated in the litter, while litter carbon was respired to CO_2. "Typically, net nitrogen release in mineral forms (ammonium and nitrate) from a given plant residue (net mineralization) only occurred after N concentration reached a critical value." (Manzoni et al. 2008). The decomposition rates could be positively related to N concentration at the first stage of decomposition, and at the same time, high N concentrations had a rate-retarding effect on lignin degradation and thus on the litter at the next stages of decomposition (Berg 2000).

The process of litter accumulation depended on many factors (Cornelissen 1996; Borg and McClaugherty 2008; Prescott 2005) that could be the reason that the relationships between carbon concentration or C/N ratio and litter stock or *L*-litter stock were not revealed.

Significant stock of readily mineralized N, high values of NO_3^- and NH_4^+ ions activity in the litter of all ecosystems indicated their potential as the sources of mineral N for plants nutrition. At the same time, low values of litter moisture (7–13%) during the summer and at the beginning of autumn could restrict availability of nutrient elements in litters.

The formation of organic carbon and nitrogen stock in upper layer of humus horizon (0–5 cm)

The rate of litter decomposition strongly influences the state of the upper humus horizon. It was found that the

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contents of total and readily nitrified nitrogen in the 0–5-cm soil layer were in the inverse relationship with their contents in the upper layer of the litter: $R = -0.78$, $P \leq 0.001$, $n = 24$ (excluding maple site) for total N; $R = -0.62$, $n = 20$ (all sites), $P \leq 0.01$ for readily nitrified nitrogen. Such relationships were not found for H-F layer of the litter. Thus, the rate of decomposition in the upper layer of the litter governs the process of nitrogen enrichment in the upper 5-cm layer of the humus horizon. In this layer, the stock of total carbon and nitrogen differed between various plant stands in the greatest degree compared to other layers. The stock of carbon decreased by 25% in maple and increased by 69, 243, and 241% in oak, pine, and fustic stands, respectively, compared to steppe soil. The stock of nitrogen decreased by 46% in maple plantation and increased by 40, 94, and 139% in oak, pine, and fustic stands, respectively.

The formation of organic C and N stocks in 5–40(60)-cm soil layer

The reduction in C stock in 5–60-cm layer was similar in all sites and amounted to about 20% of the stock in the steppe soils. The redistribution of N depended more on the wood species. In the layer 5–40-cm, it was by 35% lower in pine stand and by 20–24% lower in other plantations compared to steppe soil.

The decrease in organic C and total N contents and stocks at the depth 5–40(60) cm, in the soils of all stands, investigated most likely depended on the decrease of annual mort-root input in the forest ecosystems compared to the steppe biocoenosis. The approximate calculations confirmed our hypothesis. The root mass in 0–60-cm layer of the soil under steppe vegetation was 17.5 Mg ha^{-1} DM (Olovyannikova 1985). Supposing annual root mortality approximately equal to 80–60% of the root mass (Bazilevich and Titlyanova 2008), it meant 14–10.5 Mg ha^{-1} year^{-1} DM. According to Molchanov (1975), the mort-mass input was about 2.00 Mg ha^{-1} year^{-1} DM in 60-cm layer under 50-year-old oak wood of Tellerman forestry. This value was significantly less than in the steppe ecosystem.

In the semi-desert environment, forest and steppe litters exerted weak influence on humification process in the deeper parts of the profile. No correlation was found between the contents of organic C and total N in the litters and in the layers below 5 cm.

Litters had significant impact on the content of mobile N compounds in the humus horizon and deeper in the profile. According to our lysimetric data on nitrate content in the waters (Rzheznikova et al. 1992), NO_3^- ions were leached out from the litter into upper horizons in spring, during and after snow melting, when the litters were in a wet state. Positive correlation between NO_3^- activities values measured in spring in the litter and in the upper layers was observed. For the layers 0–5, 5–10, 10–20, 20–30, and 30–40-cm, the correlation coefficients were 0.97, 0.88, 0.88, 0.88, and 0.91 respectively, with $n = 5$, $P \leq 0.05$. This process almost stopped in other seasons due to very limited precipitations. No correlations were found between values of NO_3^- activities in the litter and in the upper horizons in autumn. The most stressful balance of mineral N forms was observed under the stand of *Acer tataricum,* it was indicated by low values of NO_3^- activities in upper horizon (0–40 cm).

Conclusions

Our results showed that organic C and N balance in forest soils depended on plant species. In the litter and 0–60-cm layer of *Quercus* stand, total C stocks were equal compared to the virgin soils. In *Pinus* and *Cotinus* stands, they increased by 58–61% and in *Acer* plantation by 21%. Total storages of N in the litter and upper horizon (0–40 cm) were equal in *Quercus*, *Pinus,* and *Acer* stands compared to virgin soils and increased by 37% in *Cotinus* plantation.

Wood species had a profound impact on the redistribution of C and N stocks between the litter and upper horizons. The increase in organic C and N stocks was observed in the litter of all artificial forest plantations compared to virgin steppe ecosystems, while in 5–40(60)-cm layer, C and N storages decreased compared to virgin soils. The magnitude of shifts in C and N storages in litter and N storages in 5–40-cm layer was governed by tree species that formed the artificial plantations. The differences in stocks of C and N between various wooden species were maximal in the layer 0–5 cm.

Significant stock of readily mineralized N and high values of NO_3^- and NH_4^+ ions activity were recorded in the litter of all forest ecosystems. Nonetheless, leaching of NO_3^- ions from the litters was possible only in spring. This fact could lead to the deficit of mineral N in forest ecosystem in other seasons, especially in soils with small stock of total N in upper horizons.

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